LATEGLACIAL AND POSTGLACIAL SHORELINE DISPLACEMENT IN THE EARN-TAY AREA AND EASTERN FIFE

BY

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I hereby declare that this thesis has been composed by me, and is based on my own work.

SUMMARY

This study of lateglacial and postglacial shorelines and shoreline displacement in the Earn-Tay-East Fife area is based on data obtained principally by the following methods: detailed morphological mapping of raised shorelines and beaches, and related fluvial and fluvioglacial features, at a scale of 1:10,560; stratigraphic investigation, involving the study of exposures, the use of site investigation bore records, and the sinking of shallow bores; accurate levelling of shoreline and other terrace features at frequent intervals along their length; and the use of a small number of radiocarbon dates. The altitudinal data were analyzed, in the light of constraints imposed by the field evidence, using height-distance diagrams, for which the most appropriate planes of projection were selected using the isobases of major shorelines as determined by trend-surface analysis. The shoreline gradients were calculated by linear regression analysis.

There is evidence of 29 stages of displacement, 17 of which are represented by shoreline fragments of sufficient number and extent to permit the calculation of meaningful gradients. Of these 17 shorelines, 16 slope down towards directions between east and southeast at gradients between 1.16 and 0.02 m/km, the gradients in general declining with decreasing age. Four phases of displacement may be recognized: the pre-Perth Readvance, Perth Readvance, Zone III Readvance, and Main Postglacial phases. In the first 3 phases, shorelines were formed in close association with glacial events: shorelines EF-1 to 6, which rise to 23-29 m O.D. at their western ends, were formed during the deglaciation of eastern Fife after the Aberdeen-Lammermuir Readvance; the Main Perth Raised Shoreline, rising to 32 m, was formed at the culmination of the Perth Readvance, and shorelines LP-1 to 4, reaching maximal altitudes of 15-19 m, were formed during the subsequent ice wastage; and buried raised shorelines, of which little is yet known, correlate with the culmination and subsequent decay of the Zone III Readvance. The almost ubiquitous Main Postglacial Raised Shoreline, which rises to 11½ m, marks the culmination of a major transgression at c.6,000 B.P., and 5 later and lower shorelines are largely confined to the vicinity of the Earn-Tay confluence.

Glacioisostatic recovery began as soon as deglaciation started, and was very rapid at first. Recovery from the maximal ice load of the last glaciation was interrupted by renewed crustal depression caused by the Perth and Zone III Readvances. The rate of uplift has declined progressively during postglacial time. Many of the shorelines are transgressive, and the sequence is most readily explained in terms of oscillatory eustatic rise and variable rates of isostatic uplift. The isobases of the 2 most prominent raised shorelines differ so markedly as to suggest a significant shift in the centre of uplift, invalidating, in this area at least, the main assumption underlying the use of shoreline relation diagrams.

PREFACE

The bulk of the fieldwork was undertaken in 1962-5 during the tenure of a D.S.I.R. research studentship at the University of Edinburgh; and additional fieldwork, financially supported by the University of Exeter, was carried out from 1966-70. This support is acknowledged with gratitude, as is the encouragement given by Professors J.W. Watson and Arthur Davies.

Particular thanks are due to Dr. J.B. Sissons, who supervised the research, and who stimulated the writer's initial interest in Quaternary geomorphology in general, and in raised shorelines in particular. The writer recalls with gratitude (and nostalgia) the period in Edinburgh when he, Dr. Sissons, and Dr. (then Mr.) D.E. Smith, worked contemporaneously on raised shorelines in their respective areas of study: many ideas and techniques were evolved during this stimulating period of collaboration and discussion.

Thanks are also due to the following: for assistance with the levelling, Miss H. Bamford, A. Brown, T. Clough, A.P. Harrild, Mrs. J. Harrild, Miss L. Harrild, Miss B. Kjølbye, I.A. Morrison, K. Paterson, J.B. Sissons, D.E. Smith, Miss R. Ward, and my wife, Ann; for cartographic assistance, Miss P. Gregory (for drawing Figs. 1.2, 3.3, 4.3, 6.1, 8.1, 8.4-8.6, 8.8, 8.9, & 9.2) and Mr. R. Fry (for expert guidance); for all the photographic work, Mr. A. Teed; and for assistance in the final assembly of the thesis, Mrs. B. Winham and Miss J. Williams.

Some of the material has previously been published in the following papers, referred to in the text, and listed in the bibliography: Sissons, Cullingford, & Smith, 1965; Sissons, Smith, & Cullingford, 1966; Cullingford & Smith, 1966; and Smith, Sissons, & Cullingford, 1969.

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CHAPTER ONE

INTRODUCTION

1. Previous work

It has long been recognized, by experts and laymen alike, that parts of Scotland have lain both beneath and above the sea in geologically-recent times, and the geological, geographical, and archaeological literature of the past 200 years has abounded in references to relative sea-level changes. No attempt will be made here to summarize this literature in detail, but rather to state briefly, as a background to the present investigation, the main trends in the evolution of ideas on (a) lateglacial and postglacial shoreline displacement in Scotland, (b) the glacial sequence, and (c) lateglacial and postglacial chronology. The detailed local literature on the Earn-Tay area and eastern Fife is referred to when appropriate in later chapters.

a) Shoreline displacement

In 1848, Chambers published his "Ancient Sea Margins", a book describing supposed raised beaches over a wide area, and dealing with the Earn-Tay-East Fife area in some detail. His simple scheme, based on the presumed horizontality of former shorelines, recognized a multiplicity of shorelines at frequent intervals up to great altitudes, but it received little support because it clearly included fluvial terraces and outcropping horizontal lava beds (Dana, 1849; A.Geikie, 1902). Moreover, his presumption of horizontality was refuted by A. Geikie's recognition in 1862 that the so-called "25 ft beach" varies in elevation between 15 and 40 ft (Geikie's figures) in eastern Scotland. Geikie suggested that differential uplift may have produced this height variation, and concluded on the basis of Roman fortifications in the Forth valley that this uplift was completed only in post-Roman times.

In view of the many discoveries of human implements in, or associated with, the postglacial raised beach deposits, there was little doubt about the uplift of the "25 ft beach" having occurred wholly within human times, but Geikie's assertion of a post-Roman uplift sparked off a lively controversy in which he was supported by Smyth (1866) and strongly attacked by Bryson (1867) and Munro (1904). Munro rejected Geikie's evidence as invalid and considered that the uplift was virtually completed by the Bronze Age.

Recent work has not finally settled the controversy over the recency of uplift. Valentin (1953), using tide gauge records, deduced that Scotland is still experiencing uplift centred on the Highlands, while Hafemann (1954) concluded on archaeological grounds that no uplift has occurred since Roman times. Comparisons between the 3 geodetic levellings of the Ordnance Survey suggest that Scotland might still be rising, although the pattern of height differences is complex, and affected by influences other than land uplift (Close, 1922; L.J. Harris & R.C.A. Edge, in communication with J.B. Sissons).

The most important single contribution to the study of Scottish raised shorelines during the last century was undoubtedly Jamieson's classic paper of 1865. On the basis of evidence in the carselands of the Forth, Tay, and Ythan, Jamieson postulated the following sequence of lateglacial and postglacial sea-level changes: (i) submergence, depositing laminated marine clays over the till; (ii) emergence, and the growth of forests and peat on the former marine tracts; (iii) submergence, depositing carse clays over the peat; and (iv) emergence, elevating the carselands to their present position. The importance of Jamieson's work lies not merely in his recognition of this succession - others had recognized it before (Anon.,1797; J.Smith,1839; Buist,1841) - as in his suggestion that the laminated clays were deposited in the proximity of wasting glacier-ice, and "that the enormous weight of ice thrown upon the land may have had something to do with this depression" (p.178). The melting of this ice would cause the land to rise again, and although Jamieson did not suggest the cause of the second submergence, he observed that the final emergence took the form of differential uplift.

This idea of depression of the crust beneath a load and its subsequent recovery, which later found expression in the theory of isostasy (Dutton,1889), was elaborated by Jamieson in 1882 and 1905, but received little attention from his British contemporaries.

The term "25 ft raised beach," which came into common use during the 1860's to describe a conspicuous feature fringing the coasts of much of Scotland, and was derived from the supposed correspondence of the inner edge of the beach with the 25 ft (8m) contour on Ordnance Survey maps, was an unfortunate term from the start. It had already been recognized that the carse clays, which rise to over 11 m O.D. in the Earn and Tay valleys and to nearly 15 m in the Forth, are the estuarine facies of this beach (Buist, 1841; Jamieson, 1865), and that the shoreline is deformed so that its height varies from well above to well below 8 m O.D. (A. Geikie, 1862; Jamieson, 1865). In 1879, the Geological Survey memoir for the Falkirk-Grangemough area (A. Geikie et al., 1879) referred also to "50 ft" and "100 ft" (15 m and 30 m) raised beaches, and this concept rapidly spread to other areas, and became generally accepted in Geological Survey publications and elsewhere, with the clear assumption that all 3 were contemporaneous features.

The sole basis of correlation was that of similar height (cf. Chambers, 1848), though the heights of beach fragments were usually only estimated from the contours, a practice that led inevitably to additional features at 75 ft (23 m) and 125 ft (38 m) being recognized in some areas. Great confusion arose between the 25 ft and 50 ft "beaches": J. Geikie (1881a, 1894) sought to explain the altitude of the Tay and Forth carselands by assigning them partly to the "50 ft" and partly to the "25 ft" beach. Dinham (1927, p.490) expressed the confusion in the Forth area by including the upper Forth carselands in the "50 ft beach", while stating that "it is . . . one with the 25 ft beach of the Edinburgh area."

Early critics of the scheme of 25, 50, and 100 ft beaches included Jamieson (1906) and W.B. Wright (1914, 1928). Jamieson drew attention to the way in which evidence was being made to accord with a preconceived idea, and Wright considered that "Since the days of T.F.Jamieson the problem of the beaches has not been attacked with any breadth of view or real insight into its meaning," and that some of the Geological Survey work was "quite unreliable and even misleading" (1928,p.99). Wright was a keen student of advances made in the study of raised shorelines in Scandinavia, where Jamieson's glacio-isostatic theory was widely accepted, and he showed how apparently complex lateglacial and postglacial oscillations of relative sea level could be explained by considering eustatic rise of sea level (first noted by Maclaren, 1842) and isostatic land uplift acting together. His "isokinetic theory of glacially controlled shorelines" (1936,1937) was claimed to explain a similar stratigraphic succession in peripheral parts of Scandinavia to that found in the Tay and Forth carselands. According to this theory, the occurrence of submergence or emergence depended on whether isostatic land uplift or eustatic rise of sea level was more rapid, and shorelines represent periods at which both land and sea were rising at the same rate. The tilt of a shoreline at the present day depends on the total amount of differential uplift since its formation, and older shorelines are, in general, more steeply inclined than younger ones. Movius (1942) appreciated the logic of this view, and produced an isobase map for a relatively steeply-sloping lateglacial raised shoreline in Scotland.

Despite these strong criticisms, the concept of 25,50, and 100 ft beaches, and the habit of correlating raised beaches over wide areas on the basis of approximately similar altitude, have continued until recently. W. Anderson (1939a) postulated lateglacial sea levels at 140 and 190 ft (43 & 58 m), in addition to those at 100, 75, and 50 ft, over much of Britain, and extended this to cover most of the northern hemisphere (1939b). More recently, Knox (1962) claimed the presence of raised beaches at 140 and 190 ft in the Howe of Fife.

Support for the '25-50-100 ft' scheme has come from some workers who have measured raised shoreline heights instead of merely estimating them. Donner (1959) found in southwestern Scotland that the "100 ft beach" has a slope of about 0.1 m/km away from a centre of uplift at Callander, while the 50,25, and 15 ft "beaches" are all horizontal. In a later paper (1963) he extended his work over most of Scotland, and concluded on the basis of 56 heights that slight tilting could be detected on all 4 "beaches", at least in the marginal areas. Other recent supporters of the scheme include King and Wheeler (1963) and McCann (1963, 1964), working in Sutherland and western Scotland respectively. The methods of all these workers will be discussed later (Chap.2), but it may be mentioned here that Donner's sites were selected from Geological Survey maps, so that his approach was to measure the 100 ft, 50 ft, 25 ft, and 15 ft "beaches", thus begging the question of whether they really exist as contemporaneous features.

The first strong critic of the standard interpretation in recent years was Sissons (1962), who suggested that lateglacial raised shorelines in Scotland have much steeper gradients than previously recognized. He demonstrated, on the basis of information in the literature, that in the Forth area, as in Scandinavia and North America, the rate of glacio-isostatic recovery was more rapid in lateglacial than in postglacial times. Older beaches should therefore be more steeply inclined than younger ones, in contrast to what the literature on the "25 ft" and "100 ft" beaches in the Forth area suggests. Sissons pointed out that the "100 ft" beach has been correlated in different areas with ice-marginal features that cannot be contemporaneous, and that major lateglacial stages have been correlated with different "beaches" by different authors.

Since 1962, the old scheme has been refuted not only by work carried out by Sissons, D.E.Smith, and the writer in the Forth-Tay region, but also by Synge and Stephens, working in western Scotland and Northern Ireland. Nevertheless, it still appears in at least one recent textbook (Small, 1970).

b) The glacial sequence

Although A.Geikie (1863) recognized that more than one ice advance had occurred in Scotland, a theme that was more fully developed by J. Geikie (1881a,1894), the first serious attempts to define major ice limits representing important glacial maxima were those of Charlesworth (1926 a & b, 1956), and Simpson (1933). The central and eastern parts of Charlesworth's 'Lammermuir-Stranraer' readvance moraine (1926b) have recently been shown to comprise fluvioglacial features of difference ages (Sissons, 1961b), and the same is demonstrably true of some of his retreat stages from the readvance limit, including those in Fife.

Recent work has supported the reality of Simpson's Perth and Loch Lomond readvances, although the actual limit of the former is farther west than that implied by Simpson (Sissons, 1963b; Chap. 5). Synge (1956) identified the Aberdeen and Dinnet readvances in northeast Scotland, correlating the former with the Perth Readvance, and agreeing with Charlesworth's (1956) correlation of the latter with the Loch Lomond Readvance.

The most recent attempt at correlating successive ice limits has been by Sissons (1964b, 1965, 1967a), who recognized the Aberdeen-Lammermuir, Perth, and Loch Lomond readvances (Fig. 1.1). Although the precise limits attained by these readvances will doubtless be altered in some areas by more detailed work, and although other readvances may have occurred that are not identified in Sissons' scheme, it nevertheless almost certainly represents the closest approximation yet to the true picture of lateglacial ice limits in Scotland.

c) Lateglacial and postglacial chronology

Lateglacial chronology in northern Britain still rests on a relatively small number of radiocarbon dates and pollen analytical studies, and on analogy with continental Europe and North America. In these latter areas, there is still considerable controversy over the detailed subdivision and chronology of the Upper Weichselian/Wisconsinan, but the general picture may be summarized as follows (e.g. Goldthwait *et al.*, 1965; Frye, Willman, & Black, 1965; van der Hammen *et al.*, 1967; Vogel & van der Hammen, 1967; Frenzel, 1967; Willman & Frye, 1970; Flint, 1971). After a

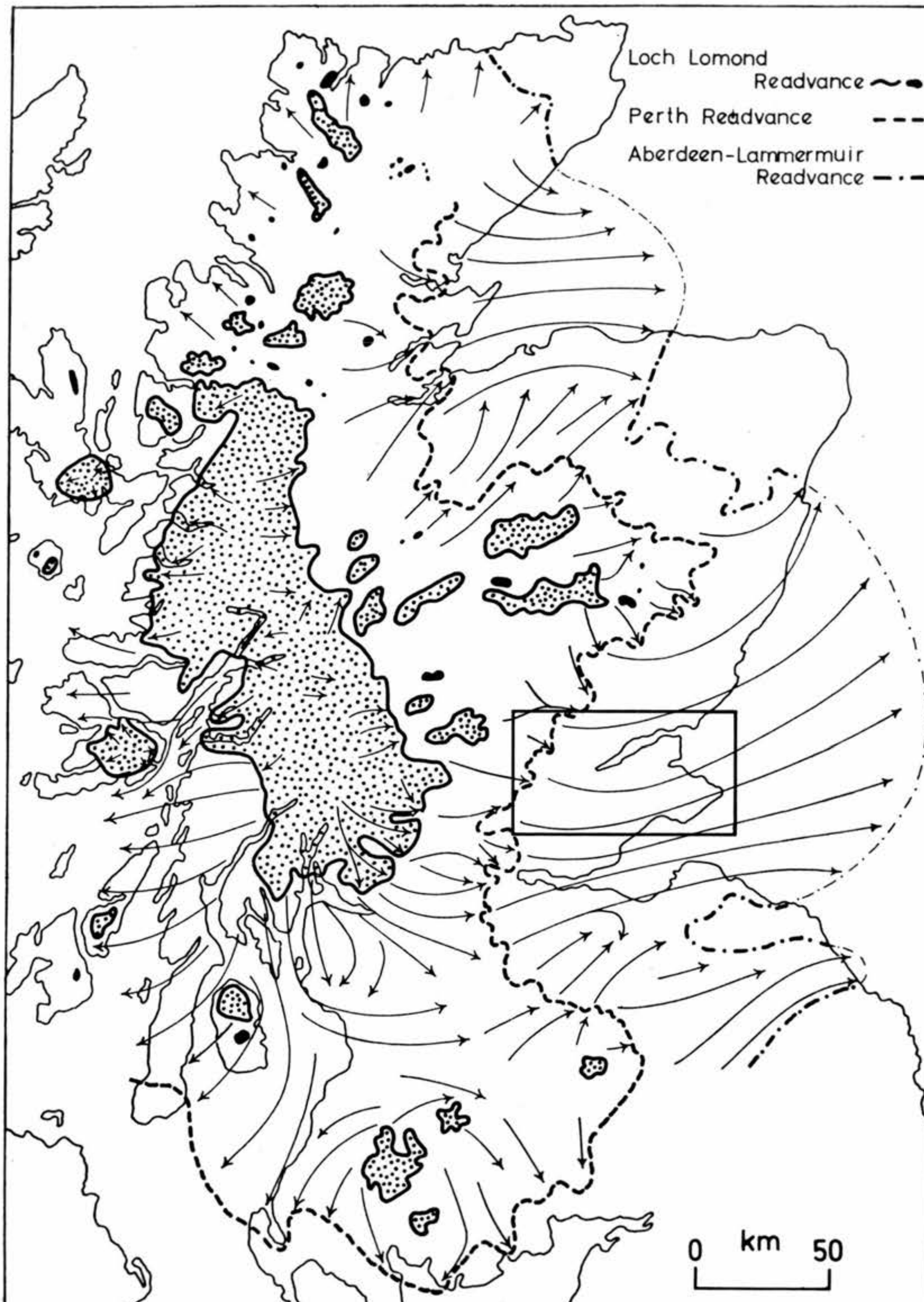

FIGURE 1.1 - Successive limits of the last ice-sheet in Scotland (after Sissons, 1967a). The rectangle encloses the area of Figure 1.2.

rather long interstadial period that may have started about 40,000 years ago, the last great build-up of the Scandinavian and North American ice sheets began about 27,000-25,000 years B.P., and reached its culmination between 20,000 and 17,000 B.P., after which there was a succession of periods of deglaciation and ice readvance until the final disappearance of the main ice masses less than 8,000 years ago.

Knowledge of the lateglacial period following the last major build-up is being greatly increased by stratigraphic work and radiocarbon dates, and more and more climatic oscillations are being recognized. Until the last few years the most usual European scheme of lateglacial oscillations, based on the pollen zone system of Jessen (1935) and Iversen (1954), and on numerous radiocarbon dates, was as follows (e.g. Tauber, 1960a & b, 1962; Hansen, 1965; de Jong, 1967; van der Hammen et al., 1967):

Zone	III	Younger Dryas stadial	11,000-10,300 B.P.
Zone	II	Allerød interstadial	11,800-11,000 B.P.
Zone	Ic	Older Dryas stadial	12,100-11,800 B.P.
Zone	Ib	Bølling interstadial	12,400-12,100 B.P.
Zone	Ia	Oldest Dryas stadial	?-12,400 B.P.

The date of the start of the Bølling interstadial has been much disputed, and has been variously put at about 12,400 B.P. (Tauber, 1960b), 12,700 B.P. (Firbas, Müller, & Münnich, 1955), and 13,300 B.P. (van der Hammen, 1957). According to van der Hammen and Vogel (1966) and Dreimanis (1966), the oldest "Bølling" dates probably refer to an interstadial preceding the Bølling, Zone Ia thus being divided as follows:

Zone Ia3	Oldest Dryas stadial	13,100-12,400 B.P.
Zone Ia2	Raunis or Susacá interstadial	13,700-13,100 B.P.
Zone Ia1	Stadial	? -13,700 B.P.

According to Mörner (1971a & b) the sequence is even more complicated, the Oldest Dryas period itself being punctuated by the Ågård interstadial. Altogether, Mörner recognizes 8 interstadials, separated by periods of ice readvance, between the culmination of the last major build-up (the Upper Pleniglacial of the Dutch workers) and the Zone III readvance, and he claims that these oscillations are globally synchronous.

Knowledge of lateglacial chronology in northern Britain is, by comparison, somewhat meagre. This may not be wholly due to lack of information, however, for it is possible that some of the minor climatic oscillations recognized in continental Europe were not clearly manifested in the vegetation record in the more oceanic climate of northern Britain. Pennington and Bonny (1970), for example, concluded from the radiocarbon-dated pollen stratigraphy of a site in the Lake District, that a rapid climatic amelioration occurred between about 13,000 and 12,700 B.P., and that between this time and the Allerød interstadial, "there was no climatic recession of sufficient amplitude to deflect the plant succession . . ." (p.873). This does not necessarily mean that there was no stadial period in Scotland equivalent to Zone Ic, but implies that the magnitude of any such deterioration was not great.

According to Sissons (1967b) the maximum of the Upper Pleniglacial build-up (c.20,000-17,000B.P.) is represented in Scotland either by the Aberdeen-Lammermuir Readvance limit, or by a more extensive former ice-cover whose limits are not known. This inference is based on a radiocarbon date of $28,140^{+480}_{-450}$ B.P. for a fossil podsol beneath glacial deposits at Teindland, Morayshire (Fitzpatrick, 1965), within the limit of the Aberdeen-Lammermuir Readvance. The date falls within the time of the long interstadial preceding the Upper Pleniglacial.

The Perth Readvance, assigned by Donner (1957) to Zone I, on the basis of pollen analyses, was attributed more precisely to Zone Ia by Sissons (1967b), on the basis of the following radiocarbon dates: $13,700^{+1300}_{-1700}$ B.P. for part of a tusk of <u>Elephas primigenius</u> from clay overlain by till ascribed to the Perth Readvance in Ayrshire; $12,814 \pm 155$ B.P. (Kirk & Godwin, 1963) for deposits postdating the Perth Readvance at Loch Droma, Ross and Cromarty; $12,940 \pm 250$ B.P. (Bishop, 1963; Moar, 1963) for material deposited during deglaciation following the Perth Readvance in Dumfriesshire. Sissons concluded that the readvance probably culminated between 13,500 and 13,000 B.P., an estimate that is supported by 6 dates for 3 marine shell samples (outer and inner parts of shells) from clays deposited in the Clyde area after the Perth Readvance, the dates ranging between $12,125 \pm 210$ and $13,020 \pm 220$ B.P. (Bishop & Dickson, 1970; Peacock, 1971).

Donner's (1957) pollen analytical dating of the Loch Lomond Readvance as Zone III (10,800-10,300 B.P.) has been confirmed by radiocarbon dates of 11,700±170 and 11,800±170 B.P. for glacier-transported marine shells incorporated into the Loch Lomond and Menteith end-moraine complexes (Sissons,1967b), implying that the readvance postdated the Allerød interstadial. 6 other dates on 5 marine shell samples from the Clyde area and Loch Creran, ranging between 11,300±300 and 11,900±250 B.P. (Baxter, Ergin, & Walton, 1969; Peacock,1971), confirm that a marine incursion occurred during the Allerød; and a shell-date of 10,560±180 B.P. from marine deposits at Greenock that were shown by algae and included terrestrial macrofossils to have been deposited in cold climatic conditions, confirms the existence of the latter during Zone III (Bishop & Dickson,1970).

Knowledge of the lateglacial chronology, as suggested by the work noted above and by other evidence from several parts of Britain (e.g. Godwin & Willis, 1959a & b; Godwin,1961), may be summarized as follows:

Zone	III	Loch Lomond Readvance	10,800–10,300 B.P.
Zone	II	Allerød interstadial	12,000–10,800 B.P.
Zone	Ic	?	?
Zone	Ib	Bølling interstadial	c.13,000– ? B.P.
Zone	Ia	Perth Readvance	? –c.13,000B.P.

These dates do not agree exactly with the continental dates listed earlier: the Allerød is about 400 years longer than is suggested by the continental data, and the interstadial dates immediately postdating the Perth Readvance fall within the period of the Oldest Dryas stadial of van der Hammen and Vogel (1966). However, in view of uncertainties about the magnitude and duration of the Bølling oscillation, and about the subdivision of Zone I in general, together with the probability that zone boundaries are only approximately synchronous, there is no reason yet to suspect the validity of the Scottish chronology.

Postglacial chronology in Britain is now well established, mainly on the basis of radiocarbon dated pollen profiles at Scaleby Moss, Cumberland, and Red Moss, Lancashire (Godwin, Walker, & Willis, 1959; Godwin, 1961; Switsur, Hall & West, 1970). The zones and their approximate dates are as follows:-

<table>
<tr><td>Zone VIII</td><td>Sub-Atlantic</td><td>2,600-0 B.P.</td><td>Climatic deterioration</td></tr>
<tr><td>Zone VIIb</td><td>Sub-Boreal</td><td>5,000-2,600 B.P.</td><td>↑</td></tr>
<tr><td>Zone VIIa</td><td>Atlantic</td><td>7,200-5,000 B.P.</td><td>CLIMATIC OPTIMUM</td></tr>
<tr><td>Zone VI</td><td rowspan="2">Boreal</td><td>9,000-7,200 B.P.</td><td>↑</td></tr>
<tr><td>Zone V</td><td>9,500-9,000 B.P.</td><td>Rapid climatic amelioration</td></tr>
<tr><td>Zone IV</td><td>Pre-Boreal</td><td>10,300-9,500 B.P.</td><td>↑</td></tr>
</table>

Palynological work in Scotland suggests a broadly similar forest history (Durno, 1956, 1957, 1959, 1967; Newey, 1965). Some zone boundaries (e.g. V/VI & VIIb/VIII) are not always so readily recognized as farther south, although in central and southeast Scotland the English zonal and subzonal criteria are clearly recognizable (Newey, 1965, 1966).

2. <u>The present investigation</u>

a) <u>Basic approach</u>

The present investigation was begun in the wake of Sissons'

(1962) exposure of the total inadequacy of the type of interpretation of Scottish raised shorelines then prevalent (sec. 1a), and in the light of his conclusion that "only research more detailed than that undertaken hitherto in Scotland will reveal the truth" (1962, p. 98). The fundamental requirements of more detailed work, as represented by the present study, were seen to be as follows:

(i) Detailed, comprehensive mapping of all identifiable raised beaches and associated fluvial and fluvioglacial features in the area of study, coupled with stratigraphic work.

(ii) Accurate altitude measurements at significant points on marine and fluviatile terraces, the measured points to represent as clearly as possible the altitude of the former shoreline or river floodplain. It was decided that terraces of insufficient morphological clarity to permit accurate measurement of a significant feature should not be measured, and that only depositional features should be heighted, in view of uncertainties regarding the altitude of rock benches in relation to contemporary sea level (e.g. Hills, 1949; Edwards, 1951), and in relation to depositional features.

(iii) A reliable and readily applicable method of distinguishing raised marine terraces from those of fluviatile origin. The need for this has not always been appreciated in previous work: although Charlesworth (1926a) realized long ago the futility of using altitudes on sloping outwash plains to indicate contemporary relative sea level, King and Wheeler (1963) used such altitudes in their indentification of "raised beaches" in Sutherland.

As will be explained later (Chap.2), requirements (ii) and (iii) were met by the same technique.

b) The area of study

The area of study includes the Earn-Tay lowlands, comprising the Carse of Gowrie, the south-coastal fringe of the Firth of Tay, the Tay valley below Stanley, and the Earn valley below Aberuthven; and the coastal fringe of eastern Fife from Fife Ness to the Tay, extending up Stratheden to just beyond Cupar (Fig.1.2). Its maximal extent from east to west is 66 km, and from south to north, 23 km. It is contiguous at Fife Ness with the area studied by D.E. Smith (1965).

The Earn-Tay lowlands occupy a basin let down between two faults in the centre of the Tay anticline, and are underlain by Upper Old Red Sandstone sediments mantled with a variable thickness of drift, the lowest recorded rockhead altitudes being -62 m O.D. at Perth, and below -65 m on the line of the Tay Road Bridge (McManus, 1966). The basin, which trends from southwest to northeast, is bounded on either side by abruptly-rising hills composed mainly of Lower Old Red Sandstone lavas - the Sidlaws to the northwest, and the Ochils to the southeast. From a width of 3-4 km near Bridge of Earn, the basin broadens northeastwards to a maximal width of 9 km before narrowing sharply at its eastern end, where it is only 2 km wide between Dundee and Newport (Fig.1.2). The present and former Tay estuaries have therefore been greatly sheltered from wave attack, and during and since deglaciation the basin has been the scene of

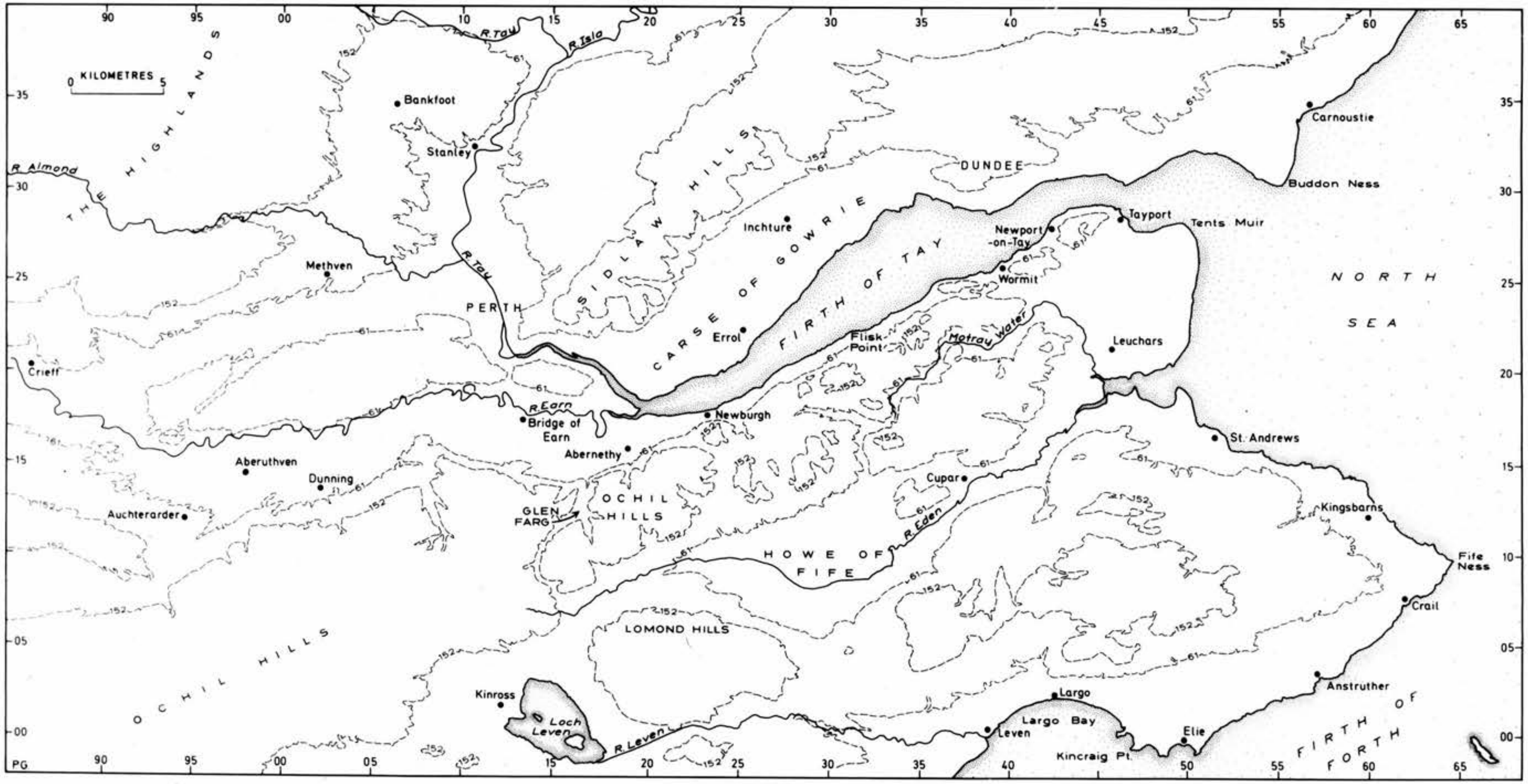

FIGURE 1.2 - The Earn - Tay area and eastern Fife. The overlay shows the subdivisions of the area of study, and the locations of the morphological maps in Chapters 3 to 6. Contours are in metres O.D.

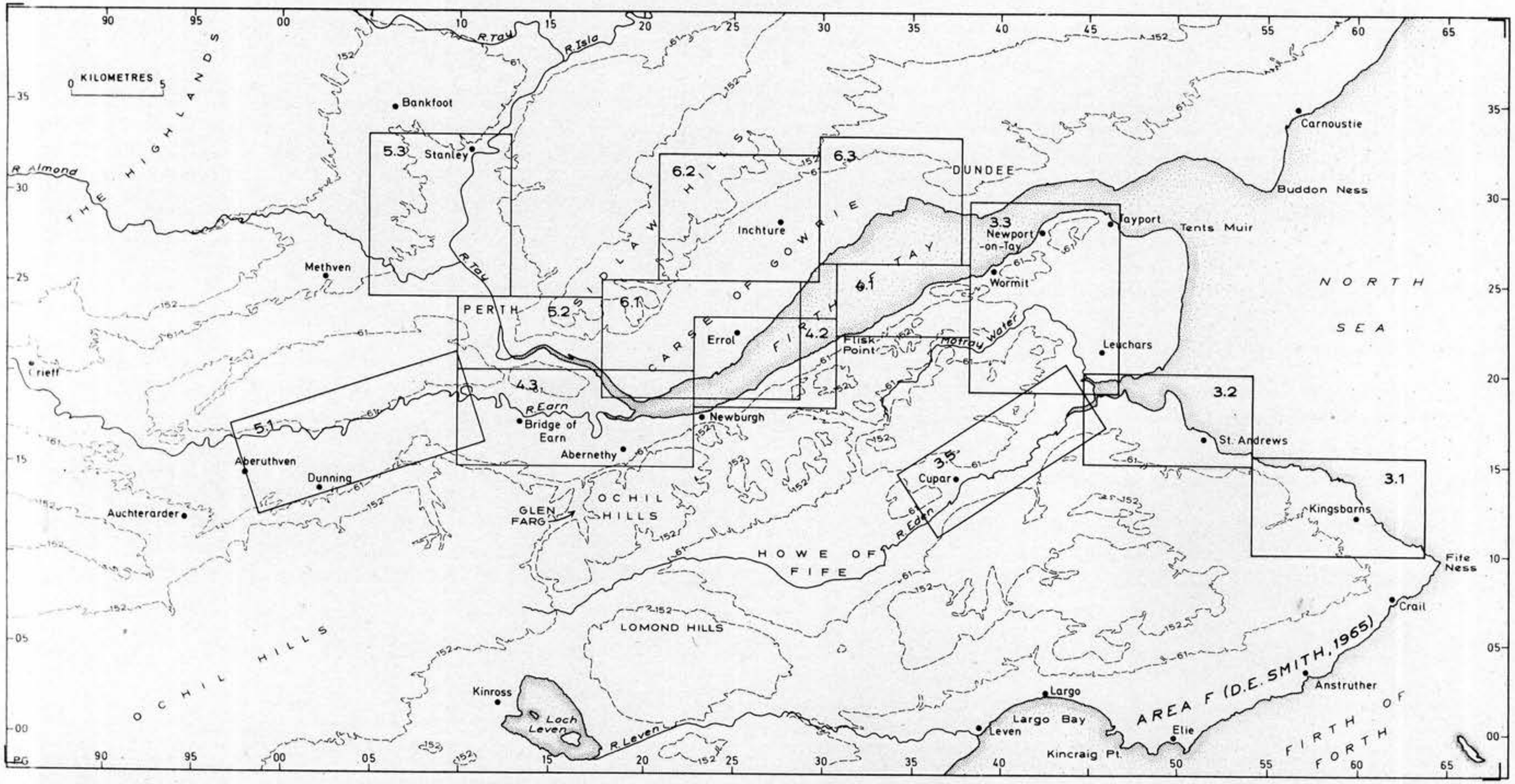

FIGURE 1.2 - The Earn - Tay area and eastern Fife. The overlay shows the subdivisions of the area of study, and the locations of the morphological maps in Chapters 3 to 6. Contours are in metres O.D.

abundant, sheltered estuarine deposition, with copious sediment supplied by two large rivers.

Like the Earn-Tay basin, Stratheden, which separates the Ochils from the Carboniferous hills of southeastern Fife, is underlain by Upper Old Red Sandstone sediments mantled with considerable thicknesses of drift, and the area of the Eden estuary has also seen copious estuarine sedimentation during and since lateglacial times. Southeastwards from the Eden, however, the scene changes, and the East Fife coast is now exposed to severe wave attack in places, although it is evident that in the past, the amount and rate of beach sedimentation have been greater, and the degree of exposure less, than at present.

For convenience of description, the study area has been subdivided into 4 smaller areas:

Area A : Fife Ness to Wormit Bay (Chap.3)

Area B : Wormit Bay to Bridge of Earn (Chap.4)

Area C : The Earn and Tay valleys (Chap.5)

Area D : The Carse of Gowrie (Chap.6)

The limits of these areas, and of the morphological maps used in chapters 3-6, are shown on Figure 1.2 (overlay).

c) Terminology

The term 'raised beach' has often been loosely applied in the literature to include a variety of depositional and erosional features. In this thesis, the term is restricted to depositional marine terraces, although for brevity it is sometimes used where 'raised estuarine deposit' might strictly be more appropriate.

'Raised shoreline' refers specifically to the concave break of slope that most nearly represents a former high water mark (Chap.2). The term 'terrace' is restricted to depositional features; 'bench' and 'platform' refer to bedrock features; and 'step' is used as a non-genetic morphological term.

The adjective 'lateglacial' is applied to the period between the culmination of the Upper Pleniglacial (possibly represented by the Aberdeen-Lammermuir Readvance) and that of the Loch Lomond or Zone III Readvance, and 'postglacial' refers to the subsequent period, extending to the present day (sec.1c). Absolute dates (principally radiocarbon dates) are expressed in years before present (B.P.), 'present' being the year 1950 A.D.

Unless otherwise stated, all altitudes are related to Ordnance Datum (Newlyn datum).

d) <u>Thesis layout</u>

The thesis falls into two main parts. In the first part (Chaps.2-6), the methods of data collection are discussed in Chapter 2, and the evidence collected is described area by area in Chapters 3 to 6. In the second part (Chaps.7-11), the methods of analysing raised shoreline height data are dealt with in Chapter 7, and the results of analysis are summarized and interpreted in Chapters 8 and 9, dealing with lateglacial and postglacial features respectively, and in Chapter 10, which is concerned with the nature, rate, and pattern of shoreline displacement in the Earn-Tay-East Fife area, and in the Forth-Tay region as a whole. Chapter 11 is a summary of the principal conclusions.

CHAPTER TWO

METHODS

This chapter is concerned with the methods by which the information used in this study was obtained, and includes some reference to methods used by other workers. The material falls into 3 main groups:

1. Morphological mapping
2. Stratigraphical investigation and mapping of deposits
3. Measurement of altitude.

1. Morphological mapping

The basis for all the work carried out in this investigation was morphological mapping of all identifiable marine, fluvial, and fluvioglacial features in the area defined in Chapter 1. The arbitrary upper limit of mapping was the 61 m contour, this altitude being exceeded only rarely, always in areas of fluvioglacial phenomena. Evidence of raised beaches and shorelines was not found above 33 m O.D. anywhere in the Earn-Tay-East Fife area.

All mapping was carried out at a scale of 1:10,560, as this was considered the smallest available scale at which adequate morphological detail could be shown, and sufficient accuracy of location obtained. Parts of the area were first studied stereoscopically on aerial photographs, at approximately the same scale. The use of aerial photographs was of great assistance in the recognition and plotting of ice-contact fluvioglacial features, but proved to be of little value in the indentification of raised beaches and other terraces, save where the backslopes are very steep.

The aim of the morphological mapping was, firstly, to plot the position and extent of all steps, regardless of origin, and to record an assessment of their suitability for measurement; and secondly, to map the relationship of the steps to each other and to other features. In describing the steps, particular attention was paid to the degree of flatness and the nature and amount of dissection of the surface, the sharpness of the break of slope between step and backslope, and the height and steepness of the latter.

Whilst morphological mapping must necessarily be somewhat subjective, varying between different observers, an attempt was made to increase objectivity by avoiding in the fieldwork stage the description of features in terms of their origin. For example, raised beaches were not mapped as such initially, but as terraces; and eskers and kames were mapped as ridges of sand and gravel, either sharp-crested or rounded in form. This approach probably saved time in the field by reducing the possibility of assumptions of origin being made, tending to influence subsequent mapping, that might later prove to be false.

It is difficult to assess the nature of the mapping undertaken by previous workers because published accounts rarely include much indication of the mapping techniques employed. In much of the work on raised beaches carried out during the latter part of the last century, mostly by the Geological Survey, mapping of deposits was the primary aim, and morphology received scant consideration, being used mainly as an aid to delimiting the different deposits. Of earlier workers, Buist (1841) and Jamieson (1865) were concerned almost solely with stratigraphy and only Chambers (1843,1848) used morphology as the foundation of his work. In recent years, Donner (1959,1963) carried out no mapping at all, having selected his widely scattered sites for measurement from Geological Survey maps, and the work of Jardine (1962,1963,1964) in southwest Scotland is based on Stratigraphy. A morphological approach was used by McCann (1961a,1964) in western Scotland, and by King and Wheeler (1963) in the north, but their mapping was selective and did not aim at complete coverage of an area.

The present work is based on the belief that detailed, unselective morphological mapping is essential for providing an adequate foundation for subsequent stratigraphic and quantitative work. Generalized or selective mapping involves the risk of missing evidence the significance of which is not appreciated at the time of mapping, and the danger of unconsciously selecting only those features that lend support to a particular hypothesis.

2. Stratigraphical investigation and mapping of deposits

Whilst some of the published information on the distribution of marine sediments in the Earn-Tay area is very useful, much of it has severe limitations, as will be apparent later (Chap.4). These shortcomings derive largely from the use of a limited and inaccurate morphological knowledge as an aid to the delimitation of surface marine deposits. For example, the area of '45-50 ft' (14-15 m) marine terrace deposits delimited by the Geological Survey in lower Strathearn and the Carse of Gowrie (1:63,360, Sheet 48,1883) includes extensive areas of both the postglacial carse silts and clays, and lateglacial sands, silts, and clays, despite the fact that these two very different classes of deposit are usually separated by a morphological break. The latter was presumably not recognized by the field surveyors, who assumed the more obvious cliff backing the lateglacial materials to be the limit of one extensive '45-50 ft' beach of variable composition. In view of such limitations in published work on the deposits, the morphological mapping in the present study was supplemented by (a) mapping of deposits, and (b) stratigraphical work.

a) Mapping of deposits

The mapping of surface materials was largely carried out as an integral part of the basic field mapping, involving both morphology and composition. The description of deposits was purely visual, without supplementary laboratory work. In areas of special difficulty where clear morphological distinctions between different deposits are lacking, systematic shallow augering to a depth of 0.9 m was carried out in order to ascertain the nature of the surface deposit. Augering was also liberally employed in cases where composition could not be reliably ascertained from surface appearance or from natural sections.

b) Stratigraphic work

Some parts of the area studied, notably the Earn valley (Chaps.4 & 5), are well endowed with clean, natural exposures up to 8 m high, affording clear and readily accessible stratigraphic information. In order to supplement the information from these sources and to obtain evidence from areas not so well endowed, use has been made of (i) site investigation bore records, and (ii) information gained from shallow bores sunk in the carse-lands by the writer.

(i) Site investigation bores An attempt has been made to assemble as complete a coverage as possible of borehole records held by local government departments, civil engineers, architects, and other business concerns. Unfortunately this information is not nearly as abundant in the Earn-Tay area as, for example, in the Forth (Sissons,1969), and only in a few cases is there sufficient concentration of information to permit detailed stratigraphic interpretation (Chaps. 4 & 5). The 308 records assembled have proved valuable at least in a descriptive sense, however, and as a complement to the borings carried out by the writer. In comparison with the latter, site investigation bore records often have limitations, some of which have been discussed by Sissons (1969). In particular, depths are usually rather more approximate than in hand boreholes; thin strata, such as the buried peat bed, are sometimes not recorded even when present; descriptions of deposits are sometimes misleading, as, for example, in the description of stoneless carse clay as 'boulder clay' in a few bores; and the ground level at the top of the borehole is not always accurately measured. In general, the records of bores sunk by rotary drilling techniques are much less reliable for recording drift stratigraphy than those sunk using percussion techniques (Chap.4). Use was made of only those bores whose location is accurately known.

(ii) Shallow hand borings A total of 142 borings (Appendix II) were carried out by the writer in the Earn-Tay carselands using a strengthened Hiller-pattern peat sampler capable of penetrating to a maximum depth of 10 m. The purpose was to investigate the nature and altitude of the material on which the postglacial carse deposits and sub-carse peat lie (Chaps. 4-6). The boreholes were located on lines extending across the carselands approximately at right angles to the main carse shoreline, at intervals of between 450 and 25 m, and no attempt was made to achieve a comprehensive coverage. For ease of location, boreholes were sunk near field boundaries where possible, and with the aid of pacing the position of each is known to within a few metres (i.e. well within the accuracy of an 8-figure National Grid reference). The altitude of the top of each bore was established by levelling to the same order of accuracy as the terrace heights (sec.3).

Little difficulty was experienced in penetrating and sampling the main mass of the carse deposits. The toughest parts of the carseland stratigraphy were found to be the top 1-1½ m of carse (the 'carse crust'), the sub-carse peat when this lay at depths greater than about 5 m, and the sub-peat materials. Occasionally, the peat was so highly compacted that it was impenetrable, and it was very rarely possible to penetrate more than about 30 cm into the sub-peat materials without damage to either the equipment or the operator. In order to reduce wear on the equipment, a spiral auger of larger diameter than the Hiller sampler was used to breach the 'carse crust'. An auger of smaller diameter than the sampler, and welded to a Hiller rod, was occasionally used to penetrate materials into which the sampler could not be forced.

Despite the vulnerability to damage and the limited depth of penetration of this equipment, it affords a rapid, cheap, and portable means of recording carseland stratigraphy, and can be operated by one person. Moreover, it enables the stratigraphy to be recorded in much more detail, and with much greater precision, than can usually be obtained with power operated rigs, and being hand operated, it allows even minor changes in composition to be felt, so that continuous sampling is not always necessary. The latter was carried out only where the stratigraphy was found to be complex, or where boring was started in a new area. It was found that a change in stratigraphy was almost invariably accompanied by a marked change in the physical effort required to achieve penetration, and this gave adequate warning of the need to sample.

3. Measurement of altitude

a) Method of measurement

The method of height measurement used was accurate instrumental levelling, using Ordnance Survey bench marks, to establish the present altitude above Ordnance Datum of each terrace fragment at frequent intervals along its length. The advantages of this method of height determination as compared with others include the following:

(i) The accuracy of measurement is far greater than is achieved by using either a barometer or a hand level. For his barometric work, Donner (1959,1963) claimed an accuracy of ±1 m using an instrument reading to 0.5 m, and King and Wheeler (1963), using a barometer that "could be read to the nearest foot", claimed an accuracy of 4 or 5 ft (1.2-1.5 m). On the basis of comparative tests between level and good surveying aneroid, Kirby (1969) concluded that "published figures for aneroid accuracy are often misleading" (p.4), and that the aneroid is not sufficiently accurate for heighting fluvial and fluvio-glacial terraces. Its inadequacy for terrace work in general was stated long ago by Johnson (1932,1944), who appreciated both the importance of terrace gradient as an indicator of origin, and the close vertical spacing of many terraces, especially in coastal areas. The range of error involved in barometer work is too great to permit an accurate measure of terrace gradient (Johnson,1932; Sissons, 1963a;Kirby,1969), and the frequency with which distinct terraces at the same locality are separated in altitude by $1\frac{1}{2}$ m or even less makes the aneroid entirely inadequate for work on lateglacial and postglacial terraces in Scotland, as demonstrated graphically by Sissons (1967a).

Measurement by hand level is probably more reliable than by barometer, but still does not approach the accuracy of ordinary levelling. McCann (1964) claimed an accuracy of about ±0.2 m in 12.2 m, and about ±0.8 m in 30 m, of vertical rise, using an Abney level set at zero, and Synge and Stephens (1966) mentioned a "computed working error" of 0.2 m in 40 m of vertical rise in their hand-level work, a figure regarded by Sissons (1967c) as a considerable underestimate. In a series of trials on a very steep slope, the writer was unable to achieve an accuracy greater than 0.2 m in only 8 m of vertical rise using an Abney level set at zero, the traverse being subsequently checked by accurate levelling. This suggests an error about 5 times greater than that claimed by Synge and Stephens.

The 3,060 heights measured during the present investigation are all accurate to within 0.1 m (0.2 ft), and most of them to within 0.05 m (0.1 ft). They were obtained using automatic levels and 14 ft (4.3 m) levelling staves graduated in units of 0.01 ft. All traverses were closed, and the largest closing error accepted, in a case of somewhat variable data, was 0.42 ft (0.13 m), although the vast majority of closing errors were 0.10 ft (0.03 m) or less. Approximately 200 heights, all in Area A, were measured as intermediate sights using surveying poles graduated in feet, the fractions of feet being estimated to the nearest 0.1 ft. The instruments were checked frequently and adjusted if necessary to maintain a truly horizontal line of collimation. The height values, originally measured in feet, were metricized, and rounded to the nearest 0.1 m.

(ii) The use of Ordnance Survey bench marks tied to the second geodetic levelling ensures that all measurements are related to a common, precisely determined, and uniform datum. Datum levels such as high water mark (as used by McCann), the barnacle line (Donner), and the upper limit of *Fucus* (Donner) or of *Enteromorpha* spp. (Synge & Stephens), vary considerably in elevation from place to place, and in many cases are not readily determinable. In the Earn-Tay area, bench marks are far more accessible to the features to be measured than any other possible datum, and even in places with few or no bench marks it was a simple task to establish temporary bench marks on convenient objects by levelling from the nearest available Ordnance Survey mark. During the course of the levelling 2 bench marks, both on bridges carrying heavy traffic, were found to have subsided, by 0.15 m and 0.05 m respectively, since they were levelled by the Ordnance Survey in 1942.

Their true altitudes were determined by checking with other bench marks, and wherever possible a point was made of checking each bench mark that was used against another at some time during the levelling work.

(iii) The dependence on weather conditions is far less than in the case of barometric measurement. Sparks (1953) found that, for the error to be 1.5 m or less when using a barometer, the wind strength must not exceed force 3 (19 km/hr), there must be little atmospheric instability, and pressure change must be fairly constant for the duration of the traverse. The wind-strength limitation for accurate levelling is much higher (force 6), and the only other limiting weather factor, considerations of personal comfort apart, is visibility.

(iv) The measurement of terrace fragments at frequent intervals along their length facilitates correlation (Chap.7) and enables fluvial and fluvioglacial terraces to be distinguished from raised beaches, as pointed out by Johnson (1932,1944) and Sissons (1963a). Almost all other workers have measured each fragment at one point or group of points only, applying one height to any one feature. This applies to those who have carried out accurate levelling (e.g. Sauramo,1958; Hyyppä 1937,1963; McCann,1966; Andrews,1970) as well as to users of less accurate methods.

A single measurement on a terrace fragment clearly means little on a feature that slopes markedly along its length, and gives no scope for identifying anomalous height values.

Moreover, it is reasonable to expect that a long stretch of continuous raised shoreline might exhibit a slope, brought out by frequent measurements along its length, that is indicative of the overall gradient of the shoreline of which it forms part. Sissons (1963a), using accurate, closely spaced height measurements, showed how some parts of the supposed '100 ft beach' in the Forth area, including one measured by Donner (1963), are in fact fluvioglacial terraces with slopes along their length of up to $5\frac{1}{2}$ m/km. In eastern Fife, terrace fragment 8 (Chap. 3, Fig. 3.2), designated by A. Geikie (1902) as part of the '100-ft beach', and described as a raised beach by Chambers (1843), slopes down eastwards from 33.7 to 24.0 m in a distance of 2.4 km, a gradient of about 4 m/km. Even slopes of this magnitude are not discernible by eye alone, and can be reliably recognized only by closely spaced measurements along the terrace. In this investigation, a standard interval between adjacent measurements of 80 m was used, dropping to 50 m in certain localities, subject of course to the points being suitable.

There is no particular threshold value of gradient that can be said to separate marine and fluvial or fluvioglacial terraces in all areas, for not only do the gradients of deformed shorelines vary greatly from place to place, but also the inclinations of river terraces vary greatly according to different hydrological circumstances at the time they were formed. However, since fluvial and fluvioglacial terraces must have undergone the same isostatic deformation as raised beaches of equivalent age in the same area, it is reasonable to expect marked differences in gradient between the two types of feature in each locality. That this is in fact the case can be illustrated by two examples from different parts of the present area. First, the steepest shoreline gradient in eastern Fife (and in the whole area of study) is approximately 1.2 m/km (Shoreline EF-1, Chap.8), and the shoreline concerned is known to be distinctly older, and to have undergone more deformation, than fluvioglacial terrace 8 referred to above, which nevertheless has a gradient more than 3 times greater. Secondly, the lowest terrace of the River Earn (Chaps.4,5, & 9) has a gradient of approximately 1.4 m/km in the 3 km between Forteviot and Broombarns, and an overall gradient over the $6\frac{1}{2}$ km between Forteviot and the present upper limit of tidal influence of about 0.9 m/km. The oldest and most steeply inclined raised shoreline in lower Strathearn has a gradient of about 0.5 m/km, distinctly lower than that of the youngest and most gently sloping river terrace in the same area.

The only obvious disadvantages of accurate levelling are the need for an assistant in the field, and the inconvenience of carrying bulky surveying equipment. Critics of the method described above object to what they regard as unnecessary precision when dealing with natural features, particularly shorelines, which can vary in altitude according to the amount of exposure to, or shelter from, wave attack, and the relative influence of erosion and deposition. Unfortunately, very little is known about the magnitude of these variations along present-day shores, but it is probable that in much of the Earn-Tay area there are, and have been, few such variations, the littoral environment being almost uniformly one of deposition, with abundant sediment supplied to a very sheltered estuary by two large rivers (and their fluvioglacial forerunners). The raised beaches of the Earn-Tay basin thus consist largely of former mudflats and sandflats, formed by quiet, estuarine sedimentation rather than by wave action. Even on the more exposed coast of eastern Fife, the well developed lateglacial shore features are mostly depositional, built from material supplied abundantly by meltwaters from the adjacent wasting ice sheet. It is also likely that wave attack was less severe then than now, due to the probability that the North Sea was frozen for a considerable part of the year.

In order to obtain a comparison between the present-day estuarine shoreline and the raised mudflats and sandflats, height measurements were taken along the edge of the present mudflats of the Eden estuary, and along the edge of the Tay sandflats east of Tayport (Chap.3). In the Eden estuary (Fig.3.2, Table 3-1), one set of 15 readings varied only between 1.6 and 1.7 m O.D., another set of 18 measurements between 1.4 and 1.8 m, and a third set of 4 heights between 1.3 and 1.4 m. The 15 heights measured at 50 m intervals east of Tayport (Fig.3.3, Table 3-5), 9 km north of the measured Eden shoreline, varied from 1.5 to 1.9 m. The total range of 48 measurements from 2 areas 9 km apart was thus 0.6 m. The consistency of readings along the main carse shoreline, about 6,000 years old, is almost as great (Chaps. 3-6). These facts suggest that the accuracy of measurement is not spurious.

The precise relationship of a measurable shoreline feature to contemporary sea level is not certain. On the present shore in northeastern Fife, the break of slope backing the mudflats is, on average, about 0.8 m below mean high water mark of ordinary spring tides, the altitude of which (2.4-2.5 m) is indicated by the surface level of the saltings backing the mudflats, (A.474,475, 771,772,926, Appendix I), and by the Admiralty tide tables for Dundee (Hydrographic Department, Admiralty,1963). The present shoreline as measured on mudflats in the Forth estuary is 0.9 to 1.2 m below mean high water mark of spring tides (Sissons, Smith, & Cullingford, 1966). It seems reasonable to assume that the raised shorelines were similarly related to former high water marks. This matter is discussed further in Chapter 10.

b) Selection of the point of measurement

The major source of error in the measurement technique employed in this investigation undoubtedly lies in the selection of the points to be measured rather than in the height values obtained, since the accuracy of the latter is indicated by the closing errors. The points were chosen as close to the junction of beach and backslope as was consistent with the avoidance of material accumulated on the beach from mass movement on the backslope, and from alluvial fans. Gullies or local depressions resulting from dissection of the terrace surface were also avoided if recognizable by eye alone. On fluvial and fluvioglacial terraces it was often necessary to take measurements well out onto the terrace surface in order to avoid the old river channel that is common at the foot of the backslope. Similarly, several raised beaches were found to have slight depressions along or very near the former shoreline, making it necessary to measure well away from the back-feature.

In the case of an extensive, flat, little-dissected raised beach backed by a steep backslope or cliff, there are few problems of selection because the limit of the downwashed material is usually clear, and measurements can be taken that approximate closely to true former shoreline values. The problems of selection increase with decreasing steepness of the backslope, and with increasing 'seaward' slope (i.e. at right angles to the shoreline) of the beach surface; the greater the seaward gradient, and the greater the area covered by talus at the foot of the backslope, the more the measurements depart from the true former shoreline values.

Further difficulties arise in the case of raised beach surfaces that are irregular, when it is necessary to decide whether the irregularities result from dissection or differential compaction of the sediments on the one hand, or from an irregular underlying topography at shallow depth on the other. In the first case the flat eminences represent the remnants of the original surface and provide the significant measuring points. In the second case the position is not so clear, and the eminences may, in fact, be slight protrusions of the underlying topography.

The process of selection used is thus visual and therefore subjective, and for the sake of consistency all the points measured were selected by the writer, who therefore held the staff, and the readings were taken by the assistant. A more objective means of obtaining a single shoreline measurement is by taking a line of levels perpendicular to the shoreline, as proposed by Tammekann (1952), starting on the backslope above the shoreline and extending well out onto the beach surface. The point nearest the base of the cliff that is unaffected by waste accumulation can thus be determined instrumentally rather than visually. If the requirement of closely spaced measurements along all terrace back-features is to be fulfilled, however, this method is extremely time-consuming, and has been used only sparingly by the writer. In cases where such cross-traverses have been carried out at locations where shoreline measurements were previously obtained by selecting points of measurement visually, the results are in very close agreement. This is shown by a cross-traverse at the eastern end of fragment T in Area D (Chap.6, Fig.6.2), the altitude determined by the cross-traverse and by a previously-measured, visually selected point being 11.7 m in each case. Several cross-traverses were used in this investigation to establish the number of terrace levels present in certain areas, mainly in the carselands.

Despite great care in selecting the most relevant points to measure, avoiding gullies, depressions, talus and the like, some heights were inevitably measured which reflect the influence of one or more of these factors. If these heights could be identified clearly by their anomalous value in comparison with their neighbours, they were excluded from the data used for analysis; if they could not be safely identified in this way, they simply contribute to the scatter of height values on the terrace concerned. The list of levelled heights (Appendix I) includes all heights levelled for this investigation, including those that have been excluded from the analysis.

CHAPTER THREE

AREA A: FIFE NESS TO WORMIT BAY

Introduction

Area A extends from Fife Ness, the easternmost promontory of Fife, to Wormit Bay, and extends inland up the Eden valley to a little beyond Cupar (Fig.1.2). Its greatest extent from south to north is 19 km, and from east to west, 29 km. In the south the arbitrary junction with D.E. Smith's (1965) Area F is National grid northing NO 10, and in the north-west the junction with Area B (Chap.4) is easting NO 385. The western limit of detailed mapping in the Eden valley is easting NO 36.

The southern part of East Fife, a "broad and undulating tract, diversified with many detached hills and ridges" (A. Geikie, 1902, p.3), is further varied by the presence of meltwater channels and mounds of glacial drift and, below about 30 m O.D., by numerous raised beach fragments.

In northeastern Fife, the landscape is dominated by the northeastern termination of the Ochil Hills, which locally do not rise much above 150 m O.D., and which are more rounded in form and more thickly clad with glacial drift than the higher parts of the chain to the south-west. Nevertheless, slopes are often steep, and bare rock is frequently exposed, displaying glacial grooves and striae. The Ochil chain is penetrated by the narrow Motray Water trough and by the Wormit Gap. The former, the floor which lies below 61 m O.D., connects Stratheden and the Howe of Fife with the Wormit Gap (Fig.1.2). The latter, a broad depression between the Firth of Tay and the Eden estuary, was the scene of abundant fluvioglacial deposition in lateglacial times.

The Eden valley, little more than $1\frac{1}{2}$ km wide to the east of Cupar, broadens westwards into the Howe of Fife, a flattish plain some 8 km across, and passes farther west into the plain of Kinross (Fig.1.2). It was the scene of abundant fluvioglacial deposition during the last deglaciation of the area.

Throughout eastern Fife, the surface composition below the 61-m contour is almost everywhere sand, or sand and gravel.

This chapter is subdivided for convenience into the following 3 sections:

I. Fife Ness to Guard Bridge (Figs.3.1 & 3.2)

II. Guard Bridge to Wormit Bay (Fig.3.3)

III. Stratheden (Fig.3.5)

I. FIFE NESS TO GUARD BRIDGE

This section includes the exposed coastline between Fife Ness and St. Andrews, and also a portion of the sheltered estuary of the River Eden between St. Andrews and Guard Bridge. The variations in exposure and degree of shelter, coupled with the detailed complexities of the Carboniferous geology, produce a great variety of landforms along the present shore, while evidence of former shorelines at higher levels is abundant.

1. Postglacial raised shorelines and associated features

a) The Main Postglacial Raised Beach and Shoreline

The most conspicuous raised beach between Fife Ness and St. Andrews is that referred to by A. Geikie (1902) as the "25-foot beach", and described here, for reasons that will be apparent later (Chap.9), as the Main Postglacial Raised Beach. It is morphologically continuous over most of this stretch of coast, and can thus be recognized as one distinct, contemporaneous feature even without the aid of height measurements.

East of St. Andrews (Figs.3.1 & 3.2) it consists of a narrow terrace, usually less than 150 m wide, between the present beach and a steep and prominent cliff. The latter, in which there are caves well above present high water mark at several places, usually rises to 15-18 m O.D., and to over 30 m west of Kittock's Den. Solid rock sometimes crops out over the whole cliff face, but more often there are varying depths of superficial deposits exposed over the top portion of the cliff face. Where these deposits are thick, mass movement has obscured the rock below, and slumped material often reaches well onto the raised beach surface, the cliff in such cases being rather less steep than where rock crops out over the whole face. At 2 localities (below beach fragments L & U, Fig.3.1) the Main Postglacial beach is separated by a low drift scarp from the next higher terrace.

The raised beach itself has a mostly irregular surface divers-

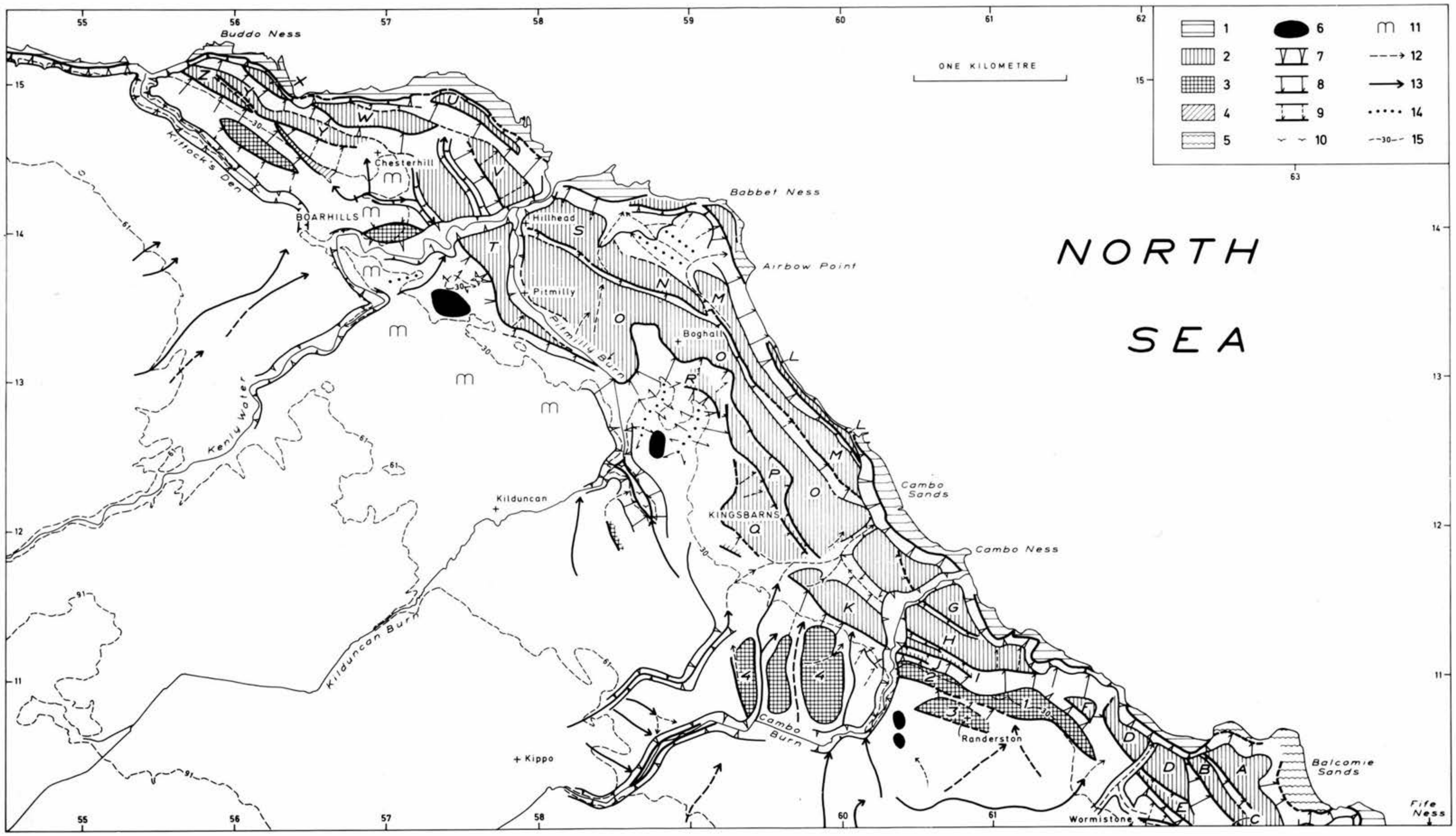

FIGURE 3.1 - Fife Ness to Kittock's Den. 1. Main Postglacial Raised Beach; 2. Lateglacial raised beach; 3. Fluvioglacial terrace; 4. Rock bench; 5. Blown sand; 6. Kettle; 7-9. Steep, moderate, and gentle slopes; 10. Alluvium; 11. Hummocky terrain; 12. Gully or dry valley; 13. Meltwater channel; 14. Ridge of sand & gravel; 15. Contour (m O.D.).

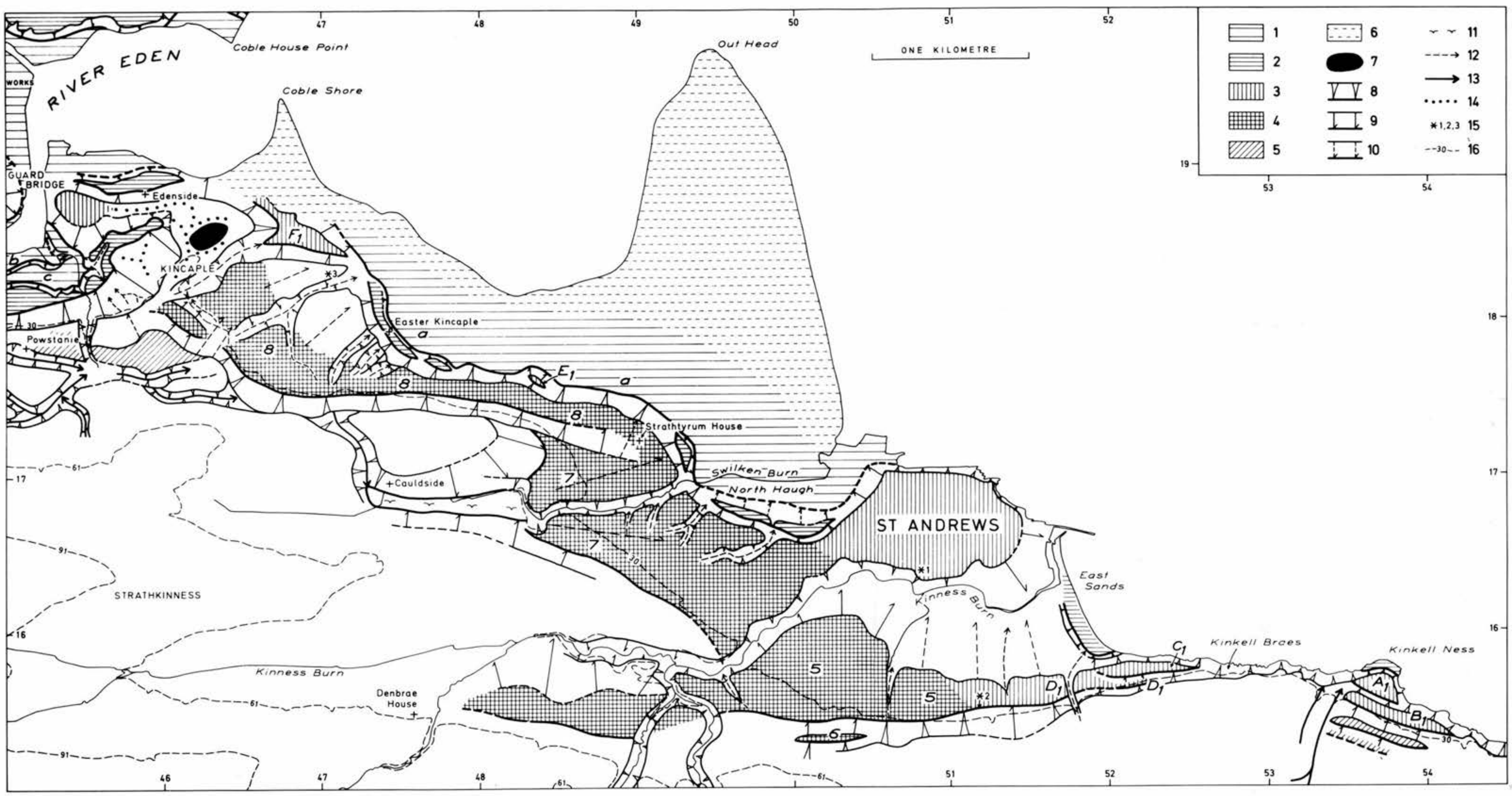

FIGURE 3.2 - Kinkell Ness to Guard Bridge. 1. Lower postglacial flat; 2. Main Postglacial Raised Beach; 3. Lateglacial raised beach; 4. Fluvioglacial terrace; 5. Step of uncertain (probably structural) origin; 6. Blown sand; 7. Closed depression; 8-10. Steep, moderate, and gentle slopes; 11. Alluvium; 12. Gully or dry valley; 13. Meltwater channel; 14. Ridge of sand or clay; 15. Exposure or set of bores referred to in text; 16. Contour (m O.D.).

ified by rock protrusions, by blown sand, and by mass movement from the cliff behind, and consists of a variable thickness of deposits resting on a rock platform. In some places the whole beach has been covered by slumped material and in others its surface has been scarred by the excavation of shelly beach material for agricultural purposes (information from farmers). Only in a few embayments is the beach a flat, regular terrace suitable for measurement, as at Wormistone, Randerston, Cambo Sands, and Chesterhill (Fig. 3.1). The altitudinal data obtained along the Main Postglacial Raised Shoreline are summarized in Table 3-1.

At many places the seaward edge of the raised beach is being cliffed by the sea, and clean, vertical sections through the beach deposits abound. A typical section (NO 6099 1146) revealed layers of well rounded pebbles and cobbles alternating with layers of comminuted shell fragments and sand containing closely packed and well preserved shells. This deposit, more than 1½ m thick at this locality, rests directly on the rock platform. Elsewhere the thickness of the deposits varies greatly, and they sometimes form only a thin veneer over the irregular rock topography of the platform. The bedrock occasionally protrudes through the beach deposits, either as low reefs or knolls, or sometimes as impressive stacks, including Buddo Rock (NO 5632 1501), the Rock and Spindle (NO 5385 1561), and Maiden's Rock (NO 5264 1579). The deposits have been almost completely removed from around the first two stacks mentioned, but the removal is far from complete around the last.

The appearance of the beach is further diversified by wind-blown sand, which forms small dunes at several places, including Balcomie, Cambo Sands (Fig.3.1), and East Sands (Fig.3.2), and which completely obscures the raised beach between Cambo Sands and Babbet Ness (Fig.3.1), where it extends some 3·5 m up the backslope. It is difficult to visualize a present-day source for this blown sand, the amount of sand in the present intertidal zone being very limited, and the sea is in fact cliffing both the blown sand and the underlying raised beach deposits. This suggests that the Main Postglacial beach deposits and associated dunes once extended farther seawards than they do now, and that the sea is at present stripping them back off the rock platform, which is probably an exhumed feature only a little modified and slightly lowered by recent marine erosion (sec.12). At St. Andrews the process of exhumation and modification is complete, and the sea is attacking the main cliff again. There is historical evidence, of varying degrees of reliability, of the inroads made by the sea at St. Andrews. A. Geikie (1902) recounted traditions concerning the former existence of grass-covered raised beach deposits on the shore platform below the castle, and "An engraving in Slezer's Theatrum Scotiae of 1693 and General Roy's map of the mid 18th century both suggest the deposits formerly extended much further seaward" (I.A. Morrison, 1961, Appendix).

Immediately west of St. Andrews (Fig.3.2) there is a marked change in the Main Postglacial Raised Beach, and other, lower, postglacial raised beaches are present. In the more sheltered environment of the Eden estuary, no rock platform is visible, the present intertidal zone is occupied by mudflats and sandflats, and the raised beach deposits are thicker and their surfaces more regular and more extensive. The prominent cliff continues as far as Easter Kincaple as a steep, relatively straight bank cut largely in drift, although solid rock crops out about 400 m east of Easter Kincaple. West of this farm the cliff diminishes in height and clarity towards Guard Bridge, and is cut wholly in lateglacial marine clay, the surface of which is greatly dissected by gullies which cut through the cliff-line but do not descend to the level of the postglacial raised beaches.

Below the cliff a flat area of sandy, shell-laden beach deposits extends seawards to the edge of the Eden estuary mudflats, between 250 and 700 m distant. There are 3 distinct postglacial raised beaches at different levels in this area, of which the highest - the Main Postglacial Raised Beach - occurs only fragmentarily along the base of the cliff. There are also 2 terrace fragments at the base of the cliff (E_1 & F_1, Fig.3.2) that are at distinctly higher levels than the Main Postglacial Raised Shoreline, and are therefore almost certainly of lateglacial age (sec.I3; Chaps.8 & 9).

At the North Haugh the flat surface of the Main Postglacial beach, which is here composed of shelly sand, does not exceed 100 m in width, from the relatively sharp junction with the steep clay bluff at the rear to the gentle irregular slope down towards the Swilken Burn at the front. Since the completion of mapping and levelling, the feature has been almost completely obscured by new university buildings.

West of Strathtyrum the Main Postglacial Beach occurs only fragmentarily and imperfectly, as a narrow ledge at Easter Kincaple and a small terrace at Edenside. South of Guard Bridge, however, it reappears as a distinct, impressively flat terrace with a maximal width of almost 250 m, and in this very sheltered location it is composed of estuarine silty clay similar to the 'carse clay' of the Earn and Tay carselands farther west (Chap.4).

The height data obtained along the Main Postglacial Raised Shoreline between Fife Ness and Guard Bridge are summarized in Table 3-1 in which the measured fragments are listed in order from southeast to northwest. This table shows that the shoreline increases in altitude towards the northwest, from about 6.4-6.6 m near Fife Ness to about 8.1 m at Guard Bridge. However, the altitudes of the small fragments at Easter Kincaple and Edenside are somewhat lower than those measured at the North Haugh and Guard Bridge, which may be an anomaly resulting from the poor development of the features concerned (Chap.9).

b) Lower postglacial raised beaches and shorelines

Below the Main Postglacial Raised Beach is an extensive raised beach, a (Fig.3.2, Table 3-1), which is encroached upon at its seaward edge by blown sand. At the North Haugh it was impossible, even before building work began, to distinguish clearly between the two beaches because of the deposition and dissection carried out by the Swilken Burn, and the encroachment of blown sand, but westward from Strathtyrum the lower beach extends as a clear feature, sharply

TABLE 3-1

POSTGLACIAL SHORELINE FRAGMENTS: FIFE NESS TO GUARD BRIDGE
(in order SE-NW)

Location	Altitude (m O.D.)		No. of hts.	Dist. m	Reference numbers
	range	mean			
Main Postglacial Raised Shoreline:					
Wormistone	6.4-6.7	6.6	4	200	A.2-5
Randerston	6.2-6.7	6.4	4	200	A.6,7,9,10
Cambo Sands	6.0-7.3	6.5	6	550	A.11-16
Chesterhill	7.4-7.6	7.5	4	150	A.117-20
North Haugh	7.3-7.9	7.6	9	500	A.29-33,40-3
(Easter Kincaple	6.7-7.0	6.9	4	150	A.71-4)
(Edenside	6.6-7.2	6.9	7	300	A.476-82)
Guard Bridge	8.0-8.3	8.1	6	400	A.787-92
Lower Postglacial Raised Shorelines:					
a.Strathtyrum-E. Kincaple	3.6-4.2	4.0	17	1,700	A.49-54,58,60,61, 66-70,75-7
b.Guard Bridge	3.8-4.3	4.0	9	400	A.773-81
c.Guard Bridge	5.5-5.7	5.6	5	350	A.782-6
Present-day Shoreline (edge of mudflats):					
Strathtyrum-E. Kincaple	1.6-1.7	1.7	15	550	A.447,448,450, 459-67,471-3
Edenside	1.4-1.8	1.6	18	750	A.483-95,498-502
Guard Bridge	1.3-1.4	1.3	4	200	A.766-9

( ) Brackets explained in Text.

defined at its inner edge, and consisting of sand and shells. Its predominantly flat surface is diversified only by broad undulations and linear depressions with an amplitude not greater than about 0.5 m, and towards Easter Kincaple it becomes increasingly silty in composition. Its altitude, measured at 17 points in a distance of 1,700 m, is 3.6–4.2 m.

South of Guard Bridge there are 2 distinct terraces, with a surface composition of silty clay, between the present mudflats and saltings and the Main Postglacial or 'main carse' beach : fragmentsb and c (Fig.3.2, Table 3–1). The altitude of b, as measured at 9 points in 400 m, is 3.8–4.3 m, and that of c is 5.5–5.7 m (5 measurements in 350 m).

Chambers (1843) regarded the beach deposits below the main cliff west of St. Andrews and south of Guard Bridge as the result of filling-in of the bay rather than of relative sea-level changes, while A. Geikie (1902) described them all as part of the "25 feet terrace", despite the existence of 2, and at one place 3, distinct terraces one above the other. The possibility that fragments a and b might be reclaimed land, or natural infill as envisaged by Chambers, is unlikely in view of the fact that the present edge of the Eden mudflats lies at only 1.3–1.8 m O.D., and the edge of the saltings at 2.4–2.5 m (Chap.2; Table 3–1). Moreover, a small area of reclaimed land at the front of fragment a, and, unlike the rest of the low-lying area, protected by a dyke, is distinctly lower than a. Also, it seems unlikely that gradual infilling of a bay without concurrent relative sea-level changes could result in a staircase of well defined terraces such as occurs south of Guard Bridge. It is therefore most likely that fragments a and b are parts of a raised beach formed in association with a relative sea level higher than the present, but lower than that responsible for the Main Postglacial Raised Shoreline. Fragment c, a very clear feature in a particularly sheltered location, provides evidence of an intermediate stage.

2. <u>The age of the shore platform of eastern Fife</u>

Reference has already been made (sec.I1a) to the impressive shore platform that truncates the complex rock structures in the present intertidal zone between Fife Ness and St. Andrews, and to the fact that it extends landwards beneath the Main Postglacial Raised Beach deposits, which were formerly more extensive than they are now. The platform thus predates the Main Postglacial Raised Beach, and has probably been only slightly modified and lowered since the beach was formed.

On the North Haugh (Fig.3.2), 27 site investigation bores sunk in preparation for new university buildings provide evidence that the rock platform is much older than the Main Postglacial Raised Beach. The boreholes were sunk in 2 groups, one comprising 18 bores in an area 400 m x 200 m near the eastern end of the North Haugh, and the other including 9 bores in an area of similar size at the western end, with a 300 m-wide strip without bores between the groups.

In the eastern group of bores, 10 were located on the surface of the Main Postglacial Raised Beach and 8 on the steep backslope. The bores on the raised beach showed 1.7-4.2 m of shelly sand, gravelly near the base, resting on bedrock, the surface of which varies in altitude between 3.3 and 5.9 m. Variations of this magnitude (about 2½ m) are common on the present intertidal platform east of St. Andrews, owing to selective marine erosion of upturned strata of varying resistance. The 8 bores on the backslope, at ground levels up to 18.5 m, showed the bedrock surface to continue landwards without significant change of level beneath an increasing thickness of sand, gravel, and laminated clay, all of lateglacial age (sec.I4 & I5). The rockhead altitude revealed by these 8 bores varies between 3.8 and 6.1 m, and is still only 4.4 m at the highest borehole position, at the cliff-top. This proves that the rock cliff backing the platform, if present, is inland of the Main Postglacial Raised Shoreline, and is covered by a much greater thickness of lateglacial material than can be explained by mass movement. Thus, if the irregular rock surface is a shore platform, which seems very likely in view of the existence of the exposed platform at St. Andrews less than 1 km away, then it must be at least of lateglacial age.

The rockhead altitude revealed in the western group of bores is more variable than in the eastern group, at 0.8-7.3 m. The bore that encountered bedrock at 0.8 m O.D. was located by the bank of the Swilken Burn, which may be the site of a buried valley cut in the bedrock. The other 8 bores reached bedrock at between 2.3 and 7.3 m O.D. The 3 bores located on the backslope showed similar lateglacial deposits to those encountered in the eastern group of bores, and 4 of the bores located on the raised beach also passed through clays and gravels between the raised beach deposits and bedrock.

3. Lateglacial raised beaches and shorelines

East of St. Andrews the rolling, broken inland topography gives way below about 30-45 m O.D. to seaward-sloping plains of sand and gravel on which are preserved the relics of former shorelines and beaches. The transition is sometimes gradual, so that the highest shorelines tend to be indistinct. In some places terraces at different levels are separated by fairly gentle slopes, and the recognition of the almost flat and often extensive beaches is in general much simpler than the precise delimitation of their shorelines, which have been obscured by mass movement. Stretches of distinct beach and backslope pass laterally into areas of amorphous, slightly irregular topography, and the fragmentation is increased by the 9-12 m deep gorges or 'dens' of the Cambo Burn, Pitmilly Burn, and Kenly Water, and by numerous shallow gullies and former watercourses. Fortunately, however, a few of the shorelines are continuous over comparatively long distances, and they usually occur in sequences one above the other, so limiting the number of possible correlations. The sequences near Fife Ness and in the Kingsbarns-Hillhead area include respectively 5 and 6 lateglacial raised beaches one above the other (Fig. 3.1).

A surface composition of sand, or sand and gravel, is common to all of the lateglacial raised beaches. In general the higher beaches are of coarser materials than the lower ones, but the use of composition as an independent criterion for the recognition and correlation of the beaches is fraught with so many difficulties that it must be regarded as unreliable in this area. This is a result partly of an overall similarity in the surface materials between the raised beaches and the fluvioglacial tracts inland, and partly of centuries of husbandry, including the still-widespread practice of carting shelly beach material inland from both the present-day and Main Postglacial beaches (sec.I1a). Shells are therefore reliable as evidence of original composition only if proved below the level of agricultural disturbance, either in sections or by augering. Occasional shell fragments were found by these means in several places.

The 5 terraces comprising the Fife Ness staircase (A-E, Fig. 3.1) are each between 400 and 800 m long and 100-300 m wide, and are separated by fairly steep bluffs. The lowest 2, A and B, are the flattest and best-preserved terraces, with sharp shorelines at 14.4-14.7 m (5 measurements in 250 m) and 16.3-17.4 m (9 points in 700 m) respectively (Table 3-2 summarizes the altitudinal data on all lateglacial raised shoreline fragments between Fife Ness and Guard Bridge); while the highest 2, D and E, form parts of a seaward-shelving plain and have rather gradual back-features at 21.5-22.4 m (9 points in 550 m) and 24.2-24.8 m (5 points in 300 m) respectively. The middle terrace of the staircase, C, is inter-

TABLE 3-2

LATEGLACIAL RAISED SHORELINE FRAGMENTS: FIFE NESS TO GUARD BRIDGE

Location	Altitude (m O.D.)		No. of hts.	Dist. m	Reference numbers
	range	mean			
A. Balcomie	14.4-14.7	14.6	5	250	A.91-5
B. Balcomie	16.3-17.4	16.8	9	700	A.96-100;F.739-42
C. Balcomie	18.3-18.9	18.6	4	300	F.743-5,747
D. Wormistone	21.5-22.4	22.0	9	550	A.102,103,290-4, 298,299
E. Wormistone	24.2-24.8	24.5	5	300	A.286-9,300
(F. Wormistone	26.2-26.7	26.4	3	100	A.295-7)
G. Randerston	17.8-18.3	18.0	5	250	A.718-22
H. Randerston	21.1-21.5	21.3	7	400	A.80-5,89
I. Randerston	23.8-24.1	23.9	4	450	A.90,639-41
J. Randerston	26.0-26.2	26.1	4	150	A.635-8
(K. Cambo	25.4-26.4	26.0	7	400	A.344-50)
L. Kingsbarns	7.7-8.4	8.1	6	500	A.18,19,21-4
M. Kingsbarns - Boghall	16.9-18.1	17.5	20	1,350	A.323-42
N. Boghall	19.1-19.7	19.4	11	500	A.686-95,697
O. Kingsbarns - Boghall	20.8-23.0	22.1	27	2,000	A.303-6,313-22, 358-66,371-4
P. Kingsbarns	22.5-23.5	23.0	11	1,050	A.301,302,307-12, 355-7
Q. Kingsbarns	25.5-25.7	25.6	3	100	A.653-5
R. Boghall	26.9-27.3	27.1	3	150	A.367-9
S. Hillhead	19.6-19.7	19.7	3	150	A.388-90
T. Pitmilly	23.9-24.4	24.1	5	300	A.391-5
U. Chesterhill	9.7- 9.8	9.7	5	300	A.123-7
V. Chesterhill	18.4-19.3	18.9	5	250	A.725,726,728-30
W. Chesterhill	21.2-21.6	21.4	5	450	A.114-6,121,122
X. Buddo Ness	19.4-20.2	19.8	3	100	A.679-81
Y. Chesterhill - Buddo Ness	24.4-25.5	24.9	10	900	A.105-10,678,685, 733,734
Z. Buddo Ness	26.2-27.0	26.5	8	350	A.112,113,673,675-7, 682,684
A_1. Kinkell Ness	20.6-21.8	21.2	4	100	A.658-61
B_1. Kinkell Ness	28.1-29.2	28.5	14	550	A.396-400,402-5,662-6
C_1. Kinkell Braes	21.8-22.4	22.1	6	250	A.406-10,414
D_1. Kinkell Braes	27.7-28.5	28.1	5	550	A.411-3,416,417
E_1. Balgove	9.7	-	1	-	A.62
F_1. Kincaple	9.4-10.3	9.8	10	500	A.698-707

( ) Brackets explained in Text

mediate in clarity between these 2 groups, and occurs wholly within Area F of D.E. Smith (1965), its shoreline altitude being 18.3-18.9 m (4 points in 300 m).

Above the western end of fragment D is a small step, F, whose back-feature lies at 26.2-26.7 m (3 heights in 100 m). Since it lies at the top of a broad rib of bedrock, however, it may well be partly of structural origin, and is therefore of doubtful value in the present context.

A staircase of 4 terraces occurs at Randerston, the lower 2 features, G and H, being the flattest and most distinct, with maximal widths exceeding 200 m, and with lengths of 400 and 600 m respectively. The altitude of G, as measured at 5 points in 250 m, is 17.8-18.3 m, and of H, 21.1-21.5 m (7 points in 400 m). A small exposure near the cliff-top in front of G (NO 6090 1140) showed sand and sub-rounded medium gravel with occasional small shell fragments. The higher 2 terraces, I and J, are no more than 50 m wide, and lie at altitudes of 23.8-24.1 m (4 heights in 450 m) and 26.0-26.2 m (4 heights in 150 m) respectively.

The area immediately northwest of the Cambo Burn gorge is dissected by broad, dry, 3 to 5 m-deep valleys, one of which occupies the position of what would have been a break of slope between flattish terraces at different levels on either side. The higher terrace, K, proved difficult to measure because its back-feature is not sharp, and because it shelves perceptibly seawards; 7 measurements in a distance of 400 m showed an altitude of 25.4-26.4 m.

The raised beaches and shorelines near Kingsbarns are the best preserved and most extensive east of St. Andrews. A broady, sandy plain descends seawards towards the main cliff in 5 steps, the highest of which, Q, is largely obscured by the village; its shoreline altitude is 25.5-25.7 m (3 heights in 100 m). The second step, P, is only 100 m or so wide, but continues for over 1 km, 11 measurements in 1,050 m showing an altitude of 22.5-23.5 m. Above the northern end of P is a short, narrow, but locally sharp step, R, with a shoreline altitude of 26.9-27.3 m (3 heights in 150 m). The middle and lowest terraces, O-T and M, have flat surfaces between 100 and 600 m across, and shelve only gently seawards, and although the former shorelines are rather vague in places they are continuous for distances of over 3 km and 1½ km respectively. The component shoreline fragments, O and T, of the middle terrace are separated by a stretch of 800 m along which measurement was not possible owing to the presence at the shoreline of the Pitmilly Burn; the altitude of O is 20.8-23.0 m (27 heights in 2 km), and of T, 23.9-24.4 m (5 heights in 300 m). The shoreline of fragment M was shown by 20 measurements in 1.4 km to lie at 16.9-18.1 m. At Babbet Ness, fragment M merges into an area of low, parallel undulations that may be beach ridges. Fragment N, 200 m wide, intervenes between M and O near Boghall, being separated from both by low but clear bluffs. Its shoreline altitude is 19.1-19.7 m (11 heights in 500 m), and is morphologically continuous with fragment S, whose shoreline lies at 19.6-19.7 m (3 heights in 150 m).

Augering on fragment O (NO 5825 1341) showed the top 0.9 m of material to be fine to medium yellow sand, with a little fine gravel. Augering to the same depth on M (NO 5979 1263) showed a composition of fine to medium sand and comminuted shell fragments, again with some fine gravel.

Fragment L is a narrow, 50 m-wide terrace at the foot of the steep cliff separating fragment M from the Main Postglacial Raised Beach. Its shoreline altitude is 7.7-8.4 m (6 heights in 500 m), only about $1\frac{1}{2}$ m higher than the Main Postglacial shoreline, from which it is separated by a clear bluff. L brings the total number of lateglacial raised beaches in the Kingsbarns staircase to 6.

Northwest of the Kenly Water gorge former watercourses confuse the terrace sequence, and although 2 terrace flats are preserved east of Chesterhill only one shoreline, V, could be measured, its altitude being 18.4-19.3 m (5 heights in 250 m). North and west of Chesterhill the 100 to 200 m-wide terraces are better preserved, although the back-features are fairly gradual. 4 shorelines, W, X, Y, and Z, were measured above the main cliff backing the Main Postglacial Raised Beach, their respective altitudes being 21.2-21.6 m (5 points in 450 m), 19.4-20.2 m (3 points in 100 m), 24.4-25.5 m (10 points in 900 m), and 26.2-27.0 m (8 points in 350 m). The associated raised beaches all have a surface composition of fairly coarse sand and gravel, and digging at the top of the cliff fronting X proved $1\frac{1}{2}$-3 m of sand over the bedrock.

Fragment U, like L (see above) intervenes between the main cliff and the Main Postglacial Raised Beach. Its altitude is 9.7-9.8 m (5 heights in 300 m).

West of Kittock's Den the rock cliffs behind the remnants of the Main Postglacial Raised Beach reach to over 30 m O.D., and evidence of lateglacial raised shorelines is absent for 1½ km as far as Kinkell Ness, where two small beaches are preserved (A_1 & B_1, Fig.3.2, Table 3-3). They are composed of sand and gravel with occasional small shell fragments. The beach surfaces, although fairly regular, slope quite strongly seawards and the breaks of slope representing the former shorelines are far from sharp; nevertheless, measurements obtained on the shorelines were reasonably consistent, the altitude of A_1 being 20.6-21.8 m (4 points in 100 m), and of B_1, 28.1-29.2 m (14 points in 550 m).

Fragment C_1 is a marked terrace up to 100 m wide, perched above 15 m-high cliffs. The back-feature of C_1 lies at 21.8-22.4 m (6 heights in 250 m), and that of D_1, upslope from C_1, at 27.7-28.5 m (5 heights in 550 m). Raised beach fragment D_1 merges westwards into terrace fragment 5, an outwash plain that broadens rapidly westwards (sec.I4); the change in gradient is imperceptible without the aid of height measurements, and the surface materials are similar.

The bedrock mass on which stands the northern part of St. Andrews is fringed and probably largely covered by raised beach material. A cliff-fall by the cathedral, visited and described by Morrison (1961), showed 3.4 m of sand with layers of shells and shingle overlying bedrock at about 18 m O.D. Unfortunately, the old city obscures the original morphology completely. A study of Ordnance Survey spot heights and bench marks (with allowance made for the heights above ground level of the latter) showed a broad uniformity of level, between 18 and 21 m O.D., of the plateau surface north of the Kinness Burn.

There are only 2 lateglacial raised beach fragments between St. Andrews and Guard Bridge, both at the base of the cliff backing the postglacial beaches, but distinctly higher than the highest of the latter. E_1 is so small that it could be heighted at only 1 point, as 9.7 m; F_1 lies at 9.4-10.3 m (10 heights in 500 m).

4. Deglaciation features

Immediately inland of the raised beaches east of Boarhills is an undulating landscape of subdued fluvioglacial forms, consisting of low, broad mounds and flattish expenses of sand and gravel with occasional closed depressions and meltwater channels (Fig.3.1). The best meltwater channels are the 3 to 6 m-deep features that form a system south of Kingsbarns, one of which is occupied by the Cambo Burn. The others are dry, and 3 of them cross a broad, flattish area of sand and gravel, the undissected remnants of which (4, Fig.3.1, Table 3-3) slope down towards the northeast from 42.9 to 41.0 m in about 500 m. Terrace fragments 1 and 2, parts of one continuous feature sloping down eastwards from 33.7 to 29.3 m in a distance of about 1.1 km, may be an eastern extension of terrace 4. Fragment 3, a small step partly obscured by farm buildings, was heighted at 3 points as 41.2-41.5 m.

TABLE 3-3

FLUVIOGLACIAL TERRACE FRAGMENTS: FIFE NESS TO GUARD BRIDGE

Location	Altitude (m O.D.) range	No. of hts.	Dist. m	Reference numbers
1. Randerston	29.3-30.4	4	300	A.952-5
2. Randerston	33.6-33.7	3	100	A.642-4
3. Randerston	41.2-41.5	3	100	A.645-7
4. Cambo	41.0-42.9	5	500	A.648-52
5. St. Andrews	28.9-37.0	22	1,400	A.425-31,592-7, 626-34
(6. St. Andrews	35.9-36.6	6	300	A.863-8)
7. St. Andrews	30.8-33.6	7	600	A.856-62
8. Strathtyrum-Kincaple	24.0-33.7	25	2,400	A.598-622

These features, and the somewhat sharper forms immediately west and northwest of Kingsbarns, do not continue into the zone of raised beaches, from which they are usually separated by a steep slope. Shallow dry valleys do continue the courses of the larger meltwater channels onto the raised beaches, but it is evident from the difference in dimensions and from the vagueness of the morphological connections that these are later developments (Chap.8).

The best-developed and best-preserved complex of fluvioglacial features east of St. Andrews flanks the Kenly Water from the Boarhills-Chesterhill area to well beyond the western edge of Figure 3.1. The landforms include many mounds and ridges, including several conical kames; hummocky terrain, in which the individual hummocks are very difficult to map (a generalized symbol is used on Fig.3.1); kettles and dead-ice hollows; and an intricate system of meltwater channels. The largest and sharpest forms lie above the 61 m contour and are therefore not shown on Figure 3.1, and many of them occur near Dunino, off the western edge of the map. Not all of the ridges and hummocky forms are of sand and gravel, for the hummocky areas at Chesterhill and around the kettle west of Pitmilly appear to be at least partly composed of dark clayey till, and although the Chesterhill features are probably partly the result of dissection by meltwater and gullying, such an origin cannot reasonably be postulated for the extensive hummocky terrain south of Pitmilly, in which clayey material is also evident. These features may possibly be of ice-pressed origin (cf. Hoppe, 1952; Gravenor & Kupsch, 1959; Stalker, 1960). The meltwater channel system is probably of subglacial origin, for it includes channels with humped longitudinal profiles, and features that run oblique to the slopes and interconnect with each other and with the Kenly gorge. Most of the channels are between 2 m and 6 m deep, but Kittock's Den, more than 30 m deep at its mouth, is also an integral part of this system despite having been subsequently modified by the small stream that occupies most of its length. The system also includes a narrow rock bench that slopes down from the end of a meltwater channel north of Boarhills to within a metre or so of raised beach fragment Y; it may even descend beneath the beach deposits, the uncertainty being caused by the sudden vagueness of the feature at the level of raised shoreline fragment Z, which becomes a clear feature 150 m away.

Terrace fragment 5 (Fig.3.2, Table 3-3) is a broad, conspicuous terrace of sand and rounded gravel, as revealed by 1.2 m-deep sections (NO 5041 1606) and by 8 site investigation bores (*2, Fig.3.2), the latter showing up to 2.7 m of sand and gravel. As stated above (sec.I3), this terrace is a morphological continuation of raised beach fragment D_1, the back-feature of the latter being approximately level at 27.7-28.5 m. Proceeding westwards, however, the back-feature rises steadily from 28.9 m to 37.0 m in a distance of about 1.4 km, a gradient of about $5\frac{1}{2}$ m/km. The westward rise in altitude continues up the Kinness Burn valley, the 46 m contour crossing the terrace surface about 600 m east of Denbrae House.

Terrace fragment 6 is a narrow step about 300 m long, over which distance its altitude is fairly consistent at 35.9–36.6 m. It is perched on the steep backslope of terrace 5.

Fragment 7 is a broad, sandy, seaward-sloping plain that is partly occupied by the western outskirts of St. Andrews. Its back-feature could be measured for only a short distance, where it declines eastwards from 33.6 to 30.8 m in 600 m. West of Strathtyrum House it overlooks the eastern end of terrace 8, a very conspicuous step whose back-feature slopes down from 33.7 to 24.0 m in a distance of 2.4 km, an overall gradient of about 4 m/km (Chap. 2).

The 3 steeply sloping terraces, 5, 7, and 8, were described by Chambers (1843) as parts of a raised beach, by A. Geikie (1902) as parts of the "100-foot" raised beach, and by Chisholm as parts of the "High Raised Beach" (1964, p.55), and as evidence of the "highest late-Glacial sea-level for which good evidence exists in north-east Fife" (1966, p.165). Besides sloping down steeply along their lengths, these terraces also shelve relatively steeply away from the backslope, and in the case of terraces 5 and 7, the direction of maximum transverse gradient is oblique to the back-feature and away from the Kinness Burn and Swilken Burn valleys respectively, as shown by the 30 m contour. It is probable that both 5 and 7 are fluvioglacial fans or aprons deposited by melt-water emanating from the valleys mentioned, 5 merging eastwards into a raised beach fragment (D_1), and 7 passing without a discernible break into the flattish area of raised beach material on which stands the northern part of St. Andrews (sec.I3). Both 5 and 7 descend to altitudes of 21 m or less at their fronts, although severe gullying may partly account for the descent to such levels. Terrace 8, also of fluvioglacial material at the surface, is only 200 m wide for much of its length, but west of Easter Kincaple it becomes much broader and is greatly dissected by dry, 3 to 5 m-deep gullies or valleys that reach back to the rear break of slope, making it unsuitable for measurement for a distance of 500 m. This dissection contributes to the steep transverse gradient of the terrace at Easter Kincaple; it slopes down to below 23 m O.D. at the front edge, where laminated marine clay is exposed (*3, Fig. 3.2; secs.I5 & III3). At Kincaple, the terrace is replaced by moundy terrain which includes at least one fully closed depression or kettle.

South of Kincaple the ground rises steeply behind terrace 8 to about 40-50 m O.D., at which altitude the gentler slopes are scored by a system of 5 to 10 m-deep meltwater channels cut in bedrock by water flowing from west to east along the slope. The downstream ends of 2 channels are truncated by the steep bluff overlooking terrace 8, the course of the higher channel being continued by the impressive 10 to 12 m-deep dry channel at Cauldside. The downstream end of the latter is distinctly lower than the apex of outwash fan 7, and the channel and fan are so disposed as to suggest that the fan material was supplied through the Cauldside channel.

The channels are probably of submarginal origin, as suggested by their trend along the slope and their proximity to a partly contemporaneous proglacial outwash fan (7), and 3 phases of development may be postulated. The first phase involved water and sediment passing through the whole system, including the Cauldside channel, and depositing outwash fan 7; the Cauldside channel thus functioning as the proglacial outlet of the submarginal system. The second phase saw the abandonment of the Cauldside channel and its upstream continuation, which now hangs above its downslope neighbour; this change presumably resulting from continued ice wastage. The third phase involved the development of the deep, rock-cut ravine that plunges straight downslope from the centre of the channel system near Powstanie, cutting off the eastward flow. This ravine, which has a maximal depth of about 15 m and contains a small stream, may have been initiated as a chute in the manner postulated by Mannerfelt (1945) and Sissons (1960, 1961a).

Although there is no other evidence to suggest the position of the ice margin, it is probable that at the time outwash fan 7 was being formed the ice-edge lay in the vicinity of the Cauldside channel. At the time terrace 5 was deposited, by water from the Kinness Burn valley, it seems likely that the ice margin was at least as far east as the Cauldside channel, or even farther east, for terrace 5 is almost certainly older than 7. It is also impossible to state precisely where the ice margin lay when terrace 8 was formed, since there is no evidence to show whether it represents the remains of a large outwash fan that has been largely destroyed by proglacial meltwater erosion, the melting of enclosed ice masses, and later marine cliffing, or whether it was formed as a mostly ice-marginal feature. The sudden broadening of the feature west of Easter Kincaple, the fact that it is dissected by dry valleys and is replaced by moundy terrain at Kincaple, and the evidence of extensive marine cliffing of lateglacial deposits at some time prior to the formation of the Main Postglacial Raised Beach (secs,I1 & I2), are all consistent with the first of these alternatives, although they do not conclusively preclude the second. If the feature is the remains of an outwash fan, the ice margin must have been near Kincaple.

5. The Lateglacial marine clay of the Eden estuary

A consistent feature of the lateglacial stratigraphy between St. Andrews and Guard Bridge is the occurrence of a laminated marine clay beneath the fluvioglacial sands and gravels, and in places beneath later marine sands. This clay is exposed in disused claypits near Easter Kincaple (*3, Fig.3.2) and at Guard Bridge (NO 4535 1878), and was encountered in boreholes in St. Andrews at *1 (Fig.3.2) and at the North Haugh (sec.I2). It was also exposed in St. Andrews in temporary sections (NO 5041 1607) that were independently examined by the writer and by Chisholm (1964), and at the North Haugh it was exposed during construction work. A similar deposit occurs north of the Eden estuary (secs. II1d & II3) and in Stratheden (sec.III3). The nature and stratigraphical position of these "brick-clays" will be considered later (sec.III3).

II. GUARD BRIDGE TO WORMIT BAY

Much of the area north of the Eden estuary is thickly mantled with fluvioglacial deposits, lateglacial and postglacial beach sediments, and wind-blown sand. The fluvioglacial deposits occupy the floor of the Wormit Gap, and their considerable thickness was shown by a borehole (NO 4050 2475) which, starting at about 29.3 m O.D. (Rice, 1961), passed through over 40 m of sands, gravels, and clays before reaching bedrock (Davidson, 1936; Lawrie & MacGregor, 1943). The lateglacial and postglacial raised beaches are flanked and encroached upon over the whole distance of 8 km between Guard Bridge and Tayport by the wind-blown sands of Tentsmuir, which cover an area of more than 24 sq. km. There is abundant evidence of a close association between wasting glacier-ice and raised beach formation.

1. The fluvioglacial landforms and deposits between Leuchars and Wormit

The ridges, mounds, and terraces of sand and gravel in the Leuchars-Wormit depression have attracted the attention of several observers, including Chambers (1848, 1867), Durham (1877), A. Geikie (1902), Charlesworth (1926b), Gregory (1926), Scott (1931), Davidson (1936), Rice (1961), Chisholm (1966), and A.R. MacGregor (1968). This great interest has resulted not only from the remarkably fresh appearance of the landforms, but also from the fact that they occur almost entirely below 45 m O.D., and are well developed to below 20 m O.D., and are therefore well within the altitudinal zone in which raised beaches have long been known to occur, both locally and elsewhere.

a) The ridges

In the northwestern part of the Wormit Gap (Fig.3.3) the principal feature of the landscape is a 3 km-long esker system, consisting of long, narrow, undulating ridges that are slightly sinuous in plan and form an anastomosing system in which the ridges bifurcate and join in complex fashion. A few of the ridges pass into or from small, flat-topped mounds and terraces. The ridges are separated by deep, fully closed depressions, some of which descend below 23 m O.D., about 23 m below the highest ridge-crests. This system is similar in many respects to those exposed by recent glacier decay in Alaska (Price, 1964,1966), and like these, it probably represents the deposits of an anastomosing subglacial and/or englacial stream system.

The composition of the eskers, as revealed in a large gravel pit (*8, Fig.3.3) and in many smaller exposures, shows the extreme variability characteristic of ice-contact deposits, and includes coarse gravel, cobbles, and boulders up to 0.6 m in diameter, with occasional larger blocks, together with masses of sand. Both the roundness of stones and the degree of stratification vary enormously between different exposures, but in general the material is sub- to well rounded, and only rudely sorted, although clear stratification, including cross-bedding, occurs locally. Quite frequently, abrupt irregular juxtapositions of bedded sand and coarse gravel were seen in the same exposure.

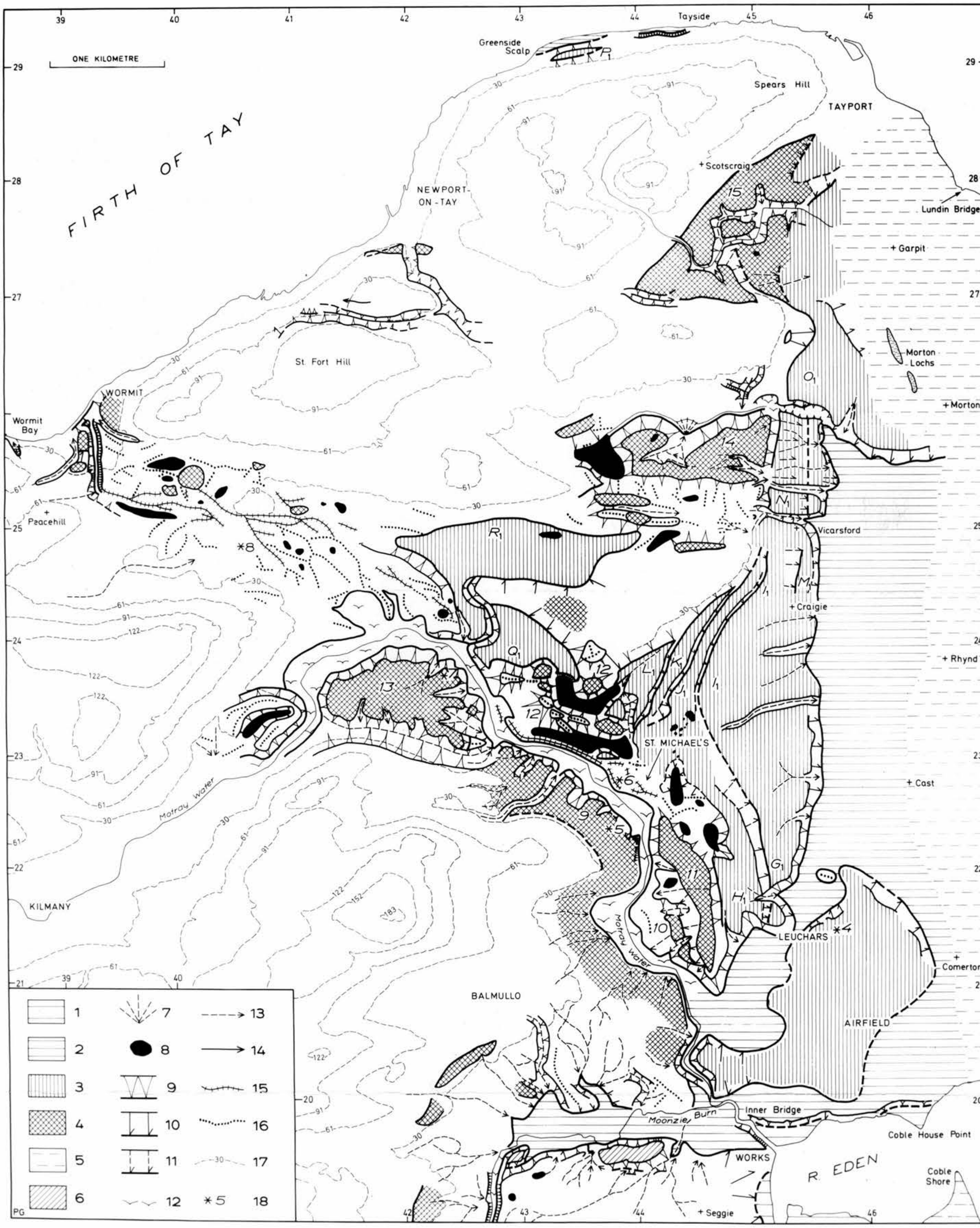

FIGURE 3.3 - Guard Bridge to Wormit Bay. 1. Lower postglacial flat; 2. Main carse; 3. Lateglacial raised beach; 4. Fluvioglacial terrace; 5. Blown sand; 6. Terrace of uncertain origin; 7. Alluvial fan; 8. Kettle; 9-11. Steep, moderate, and gentle slopes; 12. Alluvium; 13. Gully or dry valley; 14. Meltwater channel; 15. Sharp-crested ridge of sand & gravel; 16. Rounded-crested ridge of sand & gravel; 17. Contour (m O.D.); 18. Exposure or set of bores referred to in text.

In the southeastern part of the fluvioglacial assemblage the scene changes, and is dominated by large, flat-topped plateaus whose surfaces exceed 30 m O.D., by extensive flat or flattish spreads of sand and gravel at lower levels, and by steep-sided mounds or knolls, some with rounded summits and some with flat tops. The esker system is not entirely unrepresented, however, for a 9 to 12 m-high, $1\frac{1}{2}$ km-long ridge with steep sides and a sharp, undulating crest runs from the vicinity of the mounds around 12 (Fig.3.3), and, after bifurcating and rejoining near St. Michael's, passes into the lower slopes of plateau 11. The highest parts of the crest lie at about 25 m O.D., distinctly lower than the surfaces of the adjacent plateaus 11 and 13, and the esker is also much lower than the mounds at 12, from which it is separated by a long kettle. It is separated from plateau 13 and terrace 9 by the Motray Water floodplain. Rice (1961) described a section through the main (west) ridge south of the bifurcation, which showed very coarse, poorly sorted gravel with large boulders and some sand lenses, crudely bedded in an anticlinal structure. This description was verified by the writer in 1963, but by 1965, the working face of the gravel pit (*6, Fig.3.3) had reached the point of bifurcation, and showed similar material to that seen in the ridge complex to the northwest, with no trace of the anticlinal structure, but with frequent faults and other collapse structures.

b) <u>The plateaus</u>

The plateaus, which have been described in some detail by Rice (1961), are bounded on all sides by steep slopes, and have predominantly flat surfaces with only minor undulations. The most impressive of the 3 main features is plateau 13, which has a remarkably flat surface that is 1.2 km long and up to 600 m wide. The eastern and southern edges are dissected by gullies, the largest, up to 12 m deep, being those on the east, which descend to the level of the Motray flood-plain. Exposures at *7 (Fig.3.3) show that the constituent material is finer and better stratified than that of the eskers, consisting of horizontal strata of sand and medium gravel, at least near the surface. Some of the sand strata are either stoneless or include only fine gravel, and cross-bedding and minor faults occur. According to A.R. MacGregor (1968, p.133), "15 transport direction readings made on the current bedding here indicated a west-northwesterly source for the sediments", which agrees with the altitudinal evidence (sec.II1d).

The flat surface of plateau 14 is less extensive than that of 13, mainly due to gullying, which has been so severe on the northern edge that only a narrow neck of plateau surface remains, connecting more extensive portions to east and west. Deep, sinuous gullies also dissect the eastern edge, and descend to the level of the highest lateglacial raised beach at this locality (N_1). No clean exposures were seen, but the surface composition appeared similar to that of plateau 13, at least in calibre.

Plateau 11 is the least extensive of the 3 main features, with a length of more than 1.2 km, but a maximal width of only 350 m. Its flattish surface is less uniform than the other main plateau surfaces, partly because of gullying, but mainly owing to the presence of kettles and other irregularities. Although no clean exposures were seen, the surface material appeared to be more gravelly than that of the other plateaus.

The plateau surfaces, which are higher than the St. Michael's esker, also overlook many other ridges and knolls, particularly at 12 and around plateau 14, and only the highest ridges of the esker complex in the northwestern part of the Wormit Gap reach higher altitudes. These altitudinal relationships were recognized by Chambers, who explained the plateaus as the remains of "a detrital formation" produced in association with a relative sea level more than 32.6 m above the present (1848, p.54), and later referred to the ridges and plateaus as "relics of a vast sheet of alluvium" derived from "Glacial action in the Tay", on the evidence of Highland erratics in the gravels (1867, pp.549-50). The erratic content of the gravels, which include mica-schists, gneisses, quartzites, granite, and epidiorite amongst the predominant Old Red lavas and sediments, was also noted by Durham (1877) and A.R. MacGregor (1968). The plateaus and ridges were explained in terms of fluvial dissection by both Durham (1877) and Gregory (1926) and A. Geikie (1902) was the only early investigator to attribute the Wormit Gap features to fluvioglacial processes, and to regard the ridges and enclosed hollows as original constructional forms rather than as the products of dissection. Nevertheless, he assumed that, because the St. Michael's esker lies below the level of plateau 13, it must have been buried by sand and gravel and exhumed by the Motray Water. This explanation encounters the same difficulty as that of Durham and Gregory, namely, the fact that the ridge is flanked by a long kettle that could not possibly represent a former stream course.

A much more reasonable explanation of these relationships is that the ridges and plateaus are ice-contact features, and that the ridges were protected from burial under the materials forming the plateaus by the presence of glacier-ice. This is the view expressed by Rice (1961), and accepted by Chisholm (1966), MacGregor (1968), and the writer. It has already been suggested that the ridges are eskers; there is abundant evidence that the plateaus too are ice-contact features. Plateaus 11 and 14 are bounded by kettles, dead-ice hollows, and steep, irregular ice-contact slopes with alternating projections and embayments. Many of the projections along the southern edge of plateau 14 extend as mounds and ridges onto the floor of the adjacent depression, where there is a chaotic assemblage of small kames and kettles; the eastern edge of 14 was, however, cliffed by the sea in lateglacial times. The morphological evidence for an ice-contact origin is less impressive in the case of plateau 13, which is bounded on 3 sides by the Motray Water, and has undoubtedly been cliffed in places. Moreover, its fourth side is bounded by a large dry valley, regarded by A. Geikie (1902) as a former course of the Motray Water. Nevertheless, it is probable that plateau 13 was deposited in contact with decaying ice on all sides except the south, where it may have been banked against the hillside before the valley was formed by a proglacial stream. Not only is it difficult otherwise to account for the preservation, at a much lower level, of the St. Michael's esker with its flanking kettles, but the western edge of the plateau is separated only by the Motray Water from a smaller plateau, at a similar level, whose surface is almost wholly occupied by a large kettle; and the eastern edge of plateau 13 has some spurs and re-entrants that are not easily attributed to either gullying or slumping.

The recognition of the ice-contact origin of the plateaus led Rice to propose that they are crevasse fillings, with which Chisholm agreed.

c) Terraces at lower levels

Below the general level of the plateau tops there are numerous smaller flat-topped mounds, chiefly at 12, and small terraces such as terrace 10 and the small features on the eastern edge of plateau 13. There are also small terrace remnants, not suitable for measurement, at the extreme northwestern end of the Wormit Gap, a little above and a little below the 23 m contour. According to Chisholm (1966, p.166), one of these is composed of "undoubted beach gravel", but the writer could find no evidence to justify this assertion, the coarse, fairly well rounded gravel and cobbles being similar to most of the coarser deposits in the Wormit Gap.

The most impressive lower terraces are the extensive spreads of sand and gravel labelled 9 and R_1 (Fig.3.3) which, for reasons that will be stated later (sec.II1d), should perhaps be more properly classified as glaciomarine than as fluvioglacial. They are composed of finer materials than the plateaus, and were included by Rice in his "valley sand" category. The material of which terrace 9 is composed is shown in 4 pits (*5, Fig.3.3) to consist of extremely well stratified fine to medium pink sand, false bedded in places, and with interbedded thin layers of fine to medium gravel. There are also small stones scattered through the sand strata, and current ripples are well developed in places. On the whole, the beds are horizontal, although there are some very marked faults, and some gentle warping of the strata in the largest pit. In the latter, the sand is seen to overlie medium to coarse gravel with cobbles, and occasional thin beds of silt and sandy clay occur. In a 51 cm-layer of the latter, shell fragments were obtained at one stage in the workings (A.R. MacGregor, personal communication; unfortunately, the shells were lost before they could be identified).

The surface of terrace 9 is severely dissected by gullies, but that of R_1 is remarkably flat and extensive, and occupies an almost-enclosed basin the outlet of which, on the south, is only 200 m wide. South of this constriction, terrace Q_1 occurs as a continuation of R_1. It is separated from the raised beaches to the east by a large kettle, and a small kettle dimples the surface of R_1. Augering to a depth of 1.4 m (NO 4233 2476) showed the surface material of R_1 to consist of alternations of pink silty fine sand and slightly coarser yellowish sand, the latter containing fine gravel and occasional larger, rounded stones. The coarser deposit lies at the surface.

d) <u>The relation of the fluvioglacial features to sea level</u>

All previous interpretations, with the exception of Charlesworth's (1926b), have related the Wormit Gap features to a former sea level or sea levels higher than the present. A. Geikie (1902) and Scott (1931) envisaged an ice mass contemporaneous with the "100 ft beach" to explain the low-level hollows, and Davidson (1936) argued from the apparent absence of marine clays in the borehole mentioned earlier, that the fluvioglacial materials are not younger than the "100 ft beach". Gregory (1926) doubted the contemporaneity of glacier-ice in the Wormit Gap with the "100 ft beach". Rice (1961, p.122) regarded the ridges, plateaus, and "valley sand" as "representatives of three phases in the decay of an ice lobe which had advanced through the Wormit Gap into the 'hundred foot' sea". The first phase was the subglacial formation of the eskers and kames; with further ice decay, the plateaus were formed as crevasse fillings, built to the level of an englacial water-table controlled by the level of the "100 ft" sea; and in the third phase the final melting of the ice admitted the "100 ft" sea, in which was deposited the "valley sand". The latter according to Rice, extends as an irregular sheet up to about 30 m O.D., but before the hollows were completely filled-in, the relative sea level fell to about 21 m O.D., at which height was produced the kettled raised beach near St. Michael's. Chisholm accepted Rice's interpretation, and discussed the kettled beach in more detail.

Rice gave the level of the "100 ft" beach as about $36\frac{1}{2}$-$39\frac{1}{2}$ m O.D., and Chisholm (1966, p.165) stated that "The highest late-Glacial sea-level for which good evidence exists .... lies at about 120 ft O.D." (36.6 m). The writer's evidence, however, suggests that the features cited by Chisholm as evidence of this sea level are all fluvioglacial in origin (terraces 8, 15, 16, & 18; secs.

14, II2, & III1). Moreover, it is not possible to use the altitudes of the plateau surfaces themselves as evidence of contemporary sea level because they all slope down markedly towards the east and south (Fig.3.4, Table 3-4). 52 measurements spread over the surface of plateau 13 show that it slopes down fairly regularly eastwards from 40.6 to 34.7 m, a gradient of about 4.9 m/km; plateau 14 (34 heights) slopes down eastwards from 36.9 to 33.8 m at about 2.5 m/km; and plateau 11 (21 heights) slopes down southwards from 36.3 to 27.0 m at about 7.7 m/km. It is clear from these height data and from the disposition of the plateaus that they represent more than one phase of fluvioglacial deposition, and cannot be strictly contemporaneous, for plateau 13 declines eastwards to a distinctly lower altitude than the highest parts of plateaus 11 and 14, farther east (Figs.3.3 & 3.4). Plateau 13 is therefore younger than the other 2, which may or may not be contemporaneous, and taking into account the gradient of 13, it seems likely that some of the flat-topped features in the complex at 12 belong to the same phase of deposition. The most extensive of these features slopes down eastwards from 28.8 to 27.9 m in 250 m, and 2 others have surfaces at 29.4 and 27.4-27.6 m respectively (Fig.3.4, Table 3-4).

It is thus evident that the local relative sea level during the formation of the plateaus was not about 36½ m O.D. as suggested by Rice and Chisholm but was 33.8 m or less when plateau 14 was formed, 27.0 m or less when plateau 11 was formed, and 27.4 m or less when plateau 13 and the associated mounds at 12 were formed. The

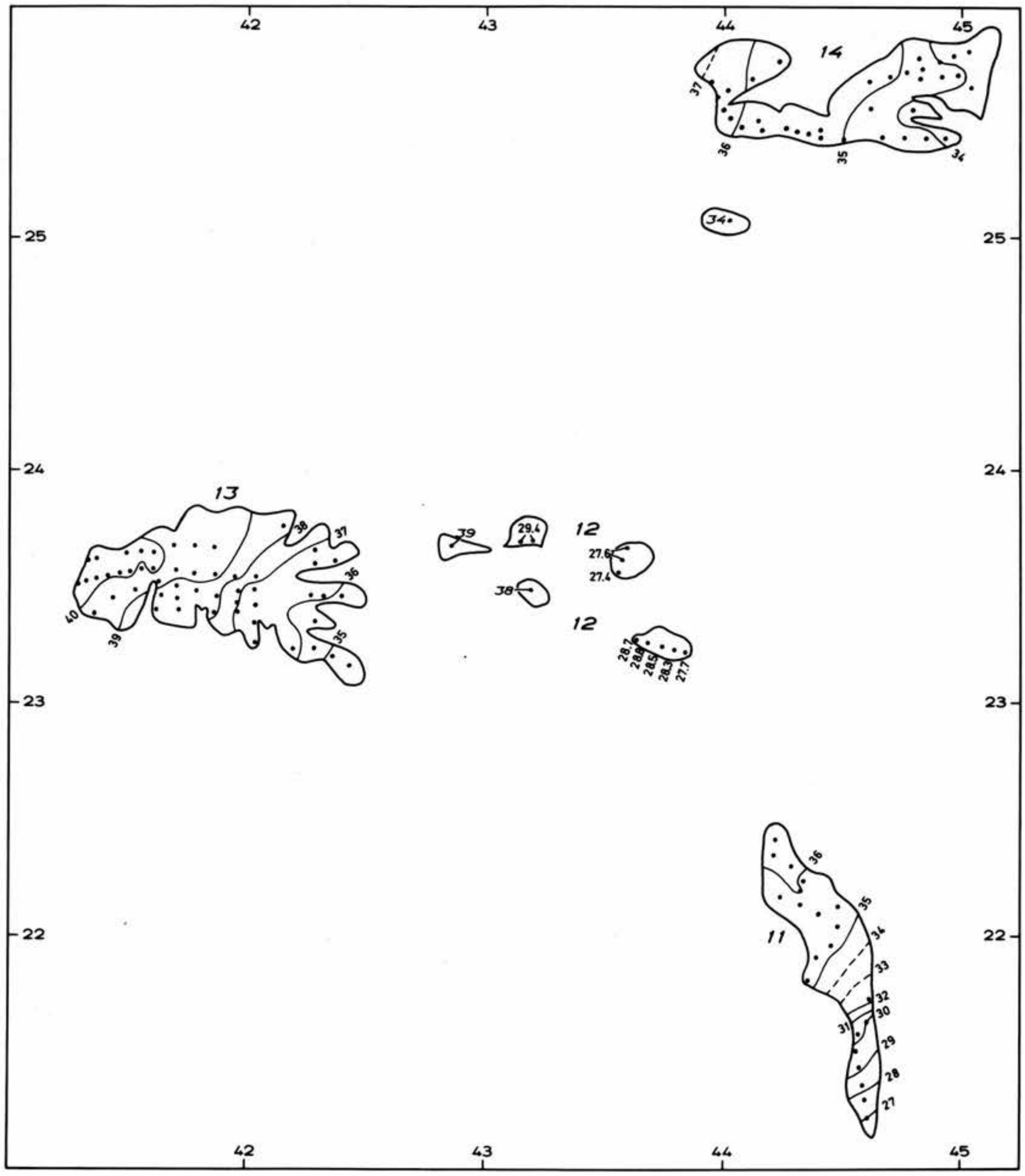

FIGURE 3.4 - Height data on plateaus 11, 13, and 14, and on the Strathburn mounds (12). The dots are the positions of measured heights, and the lines are contours (m O.D.) on the plateau tops.

TABLE 3-4

LATEGLACIAL TERRACE FRAGMENTS: GUARD BRIDGE TO WORMIT BAY

Location	Altitude (m O.D.) range	Altitude (m O.D.) mean	No. of hts.	Dist. m	Reference numbers
Lateglacial raised shore-line fragments:					
G_1. Leuchars	15.5-15.8	15.7	6	400	A.191-6
H_1. Leuchars	22.8-23.1	23.0	5	300	A.185-9
I_1. St. Michael's - Vicarsford	15.6-16.4	16.0	15	950	A.180-4,213-22
J_1. Craigie Hill	17.6-18.0	17.8	5	850	A.210-2,280,281
K_1. Craigie Hill	19.6-20.4	20.0	14	700	A.197-206,209,273-5
(L_1. Craigie Hill	22.5-23.1	22.7	9	800	A.264,267-71,916-8)
M_1. Craigie - Vicarsford	10.3-10.7	10.5	3	150	A.177-9
N_1. Cotton	15.5-15.8	15.7	3	150	A.282-4
O_1. Lawhouses	16.0-17.0	16.6	9	700	A.503-6,511-5
(P_1. Greenside Scalp	17.3-17.9	17.C	7	150	A.432-8)
Q_1. Strathburn	20.9-21.6	21.3	5	350	A.888-91,915
R_1. Morendy	20.5-21.7	21.2	15	1,200	A.869-83
Fluvioglacial terrace frag-ments:					
(9. Brackmont Mill	24.7-26.9	-	3	400	A.935-7)
10. Gallow Hill	25.2-26.5	-	4	200	A.245-8
11. Gallow Hill	27.0-36.3	-	21	1,200	A.238-44,249-62
a.	29.4	-	2	50	A.900,901
12. Strathburn b.	27.4-27.6	-	3	100	A.892-4
c.	27.9-28.8	-	5	200	A.895-9
13. North Straiton	34.7-40.6	-	52	1,150	A.552-91,902-13
14. Cowbakie Hill	33.8-36.9	-	34	1,100	A.518-51
15. Scotscraig	23.7-43.1	-	14	1,500	A.708-10,712-7, 851-5

( ) Brackets explained in Text.

shoreline altitudes of the highest raised beach fragments in the vicinity, H_1 and L_1 (sec.II3), are 22.8–23.1 m and 22.5–23.1 m respectively. Both beaches obviously postdate the plateaus and associated features (Fig.3.3), but are probably closely related to terraces 9, 10, Q_1, and R_1.

The surface of terrace 9 has been so largely destroyed by gullies and sandpits that it was measured at only 3 points in 400 m (Table 3–4). Together with an Ordnance Survey bench mark, the heights suggest a southeastward slope down from about 27 m to about 24½ m in just over 1 km. Terrace fragment 10, across the Motray valley from 9, and almost certainly contemporaneous, slopes down southwards from 26.5 to 25.2 m in 200 m (4 heights, Table 3–4). In view of the proximity of raised beach fragments H_1 and L_1, the relatively calm environment of deposition indicated by the terrace deposits, and the occurrence of shells (sec.II1c), the deposits of terrace 9 (and probably 10) may be regarded as fine grade outwash discharged into the sea at about the same time as H_1 and L_1 were formed, or slightly earlier. The faults and distortions in the bedding imply the proximity of ice when 9 was formed, and kettles show that the raised beach fragments were formed in intimate association with decaying glacier-ice (Fig.3.3).

The writer found no evidence that the "valley sand", as represented by the materials of terrace 9, reaches an altitude of 30 m as stated by Rice. The irregular sheet of sand and gravel that reaches above 30 m O.D. near Balmullo is much coarser than the terrace 9 deposits, and the irregular surface form results largely from intense dissection by an intricate system of 3 to 5 m-deep valleys or gullies which cross both the coarser deposits (probably of 'plateau' age) and the terrace 9 materials and descend to the level of the Motray floodplain on the north, and below the level of the carse deposits on the south (Fig.3.3, sec.II4).

5 heights along the back-feature of terrace Q_1 show an eastward slope from 21.6 to 20.9 m in 350 m (Table 3-4), although this slope may be partly caused by the proximity of the large kettle that separates Q_1 and L_1. 15 heights along the western and northern edges of R_1 show a northeastward slope from 21.7 to 20.5 m in 1.2 km, although there is no outlet from the basin in the east. As with terrace 9, the nature of the deposits suggests a calm environment of deposition (sec.II1c), and it seems reasonable to regard that environment as an inlet of the sea, probably postdating beach fragments H_1 and L_1 (Chap.8). The eastward slope of R_1 may be partly the result of sediment supply from the northwest, and partly the result of isostatic tilting.

e) The sequence of events

On the basis of the above evidence, it is suggested that the sequence of events in the evolution of the fluvioglacial and glaciomarine landforms and deposits between Leuchars and Wormit was as follows.

(i) The first features to form were the eskers, deposited in subglacial tunnels by meltwater flowing from northwest to southeast.

(ii) As ice decay proceeded, and the ice began to break up into detached masses, large volumes of fluvioglacial material from the northwest and west were poured into and over the ice, forming the plateaus and the higher kames at 12 and around plateau 14. At the end of this phase relative sea level in the neighbourhood was about 27 m O.D. or less. This stage was probably partly contemporaneous with the esker formation, for it appears that plateau 11 was fed, at least in its early stages, by the stream that deposited the St. Michael's esker. At least two phases of deposition are represented by the plateaus and associated features, and the present relationship of the plateaus to other ice-contact features may be regarded as an extreme form of pitted outwash. The present limits of the outwash remnants were determined both by the continued presence of large ice masses, which protected the eskers and the lower kames from burial, and, to a much lesser estent, by the erosional activity of proglacial meltwaters.

(iii) With further wastage of the ice, progressively finer materials were conveyed to the sea, which, although it was being admitted into some parts of the fluvioglacial complex by the melting of ice masses, was gradually falling in its relative level due to land uplift (Chaps. 8 & 10). Terrace 9 is composed of material poured into the sea when it was at a level, relative to the land, that was similar to or slightly higher than that represented by the highest raised shoreline in the vicinity (about 23 m O.D.), while terraces Q_1 and R_1 are composed of material deposited in the sea as it receded from this level.

(iv) Some ice masses outlasted all these events, as shown by the large kettles that separate raised beach fragments H_1 and L_1 from the fluvioglacial features (sec.II3). The final stages in the evolution of the landforms saw the melting of these residual ice masses, and the dissection of many of the landforms, both by meltwaters from the residual ice masses, and by later gullying, which in the case of the more easily erodible deposits was intense.

2. Other fluvioglacial features

Terrace 15 (Fig.3.3) is an eastward-sloping plain of sand and gravel, interpreted here as a fluvioglacial fan, but cited by Chisholm (1966, p.170) as evidence of "the late-Glacial raised beach", rising to "the normal limit for the area, at about 120 ft O.D." (36½ m). The northern edge slopes down continuously from 43.1 to 23.7 m in about 1.5 km, a gradient of almost 13 m/km. This is the second highest terrace gradient measured in this investigation. Although predominantly flat, the sloping surface of the fan has minor undulations (interpreted by Chisholm as storm-beaches), and is dissected by a 3 to 6 m-deep incised stream channel. The surface composition is slightly rounded fine to medium gravel, becoming coarser towards the apex of the fan, where there is a short length of channel, cut 3 to 6 m in rock, at the eastern end of a col.

There is no definite evidence to show how this fan relates to the Wormit Gap features, but it may be broadly contemporaneous with plateau 14. There is at least one vague break of slope on its surface, below 23 m O.D., which probably represents a former shoreline, but it was too indistinct to measure.

The only other major fluvioglacial features are a large melt-water channel cut 15 m in rock behind Newport and, at right angles to the eastern end of this channel, a 10 m-deep gorge that plunges steeply downslope. The former has a humped long-profile, and is directly in line with the col referred to above; it may mark the subglacial course of the waters that deposited fan 15.

3. Lateglacial raised shorelines and beaches

A broad, sandy plain descends gently eastwards from the edge of the fluvioglacial area over the whole distance (6½ km) between Leuchars and Tayport, reaching a maximal width of 1½ km east of St. Michael's. The existence of more than one level in this plain was recognized by both Rice and Chisholm, but the latter (1966, p.169) asserted that it "cannot be subdivided because the slope is broken by only a few, inconstant back-features". Whilst it is true that the shorelines are sometimes indistinct or even unrecognizable, 5 definite levels are represented, 2 of which are delimited by particularly clear former shorelines; and one of them is morphologically continuous, except for minor breaks caused by gullies and small valleys, for 5 km between Leuchars and fan 15.

One of the clearest shorelines is the highest, comprising 2 fragments, H_1 and L_1 (Fig.3.3, Table 3-4, sec.II1d). Beach fragment H_1 is a very flat terrace up to 500 m wide, backed by a sharp break of slope that was measured as 22.8–23.1 m (5 points in 300 m). Northwards, this beach is largely replaced by a complex of large kettles, comprising 4 separate, fully closed hollows, the largest of which descends to below 12 m O.D. and is therefore more than 10 m deep. According to Chisholm the lowest point on the rim of this largest kettle lies at 17.4 m. The point he measured is, in fact, still within the kettle complex, but the lowest point on the outer rim of the latter, near St. Michael's, lies at about 16.8 m, indicating that the ice finally melted only after relative sea level had locally fallen to that level. This means that the dead ice masses outlasted the formation of 3 successive raised beaches, for fragments L_1, K_1, and J_1, which occur in a staircase, all lie at higher levels.

Fragment L_1, the highest in the St. Michael's staircase, was shown by 9 measurements in 800 m to lie at an altitude of 22.5-23.1 m, although the heights are probably slightly lower than the original shoreline because the latter is occupied by a gully, and by part of the kettle that separates L_1 from Q_1 (sec.II1d), so that the measurements were made well out onto the terrace surface. A low bluff separates L_1 from the next member of the staircase, K_1, the shoreline of which was measured at 19.6-20.4 m (14 heights in 700 m). The eastern slope of Craigie Hill forms the backslope of K_1 at the northern end of the latter. A low but distinct bluff separates K_1 from a third beach, J_1, the back-feature of which also converges northwards on Craigie Hill. The shoreline was heighted at 5 points in 850 m as 17.6-18.0 m.

A shallow trench and several deep pits excavated across raised beach fragment H_1 and across the kettle complex to St. Michaels, which were examined by the writer and by Chisholm, who described them in his paper (1966, p.169), all showed 1.5-2.1 m of pink or reddish flat-bedded sand consisting of alternating thin laminae (13 mm or less) of fine and medium calibre. This deposit, interpreted by Chisholm as beach sand, according to criteria recognized by W.O. Thompson (1937), was undisturbed in a pit (NO 4429 2262) located in the northernmost kettle, which occupies part of raised beach fragment J_1, although collapse structures were evident where the trench crossed the rim of the largest kettle. The flat-bedded sands were seen to rest on gravel in 3 pits on the unkettled part of fragment H_1, and according to Chisholm (who evidently saw the pits when they were deeper than when seen by the writer), these deposits "rested on a curious mixture of sands, silts, and red silty clays", the latter being similar in appearance to the Stratheden 'brick-clays' (sec.III3). These mixed sediments were 0.9-1.5 m thick, and rested in turn on sands and gravels similar to those in the St. Michael's esker pit (*6, Fig.3.3; sec.II1a). Chisholm interpreted the whole sequence as representing a succession of fluvioglacial, off-shore, and beach sedimentation, "possibly under the influence of a falling sea-level".

The longest and clearest lateglacial raised shoreline comprises fragments G_1, I_1, N_1, and O_1, and although it was unmeasurable in places, because of vagueness, woodland, or gullies, its morphological continuity between Leuchars and Tayport is clear. The 33 heights obtained over a distance of 5 km vary between 15.5 and 17.0 m, the shoreline altitude increasing slightly northwards (Table 3-4). M_1 is a flattish step interrupting the rather gentle slope down from fragment I_1; its shoreline, which continues across the gullied area north of Vicarsford, could be heighted at only 3 points in 150 m as 10.3–10.7 m.

The eastern part of Leuchars village lies on a detached portion of the lateglacial beach plain, the surface of which includes flattish areas at various levels between 10½ and 18½ m O.D., although there are no clear breaks of slope. 4 site investigation bores at *4 (Fig.3.3) passed through 3 m of fine-medium sand with some gravel, and one of them, sunk to a depth of 6.1 m, penetrated a 2.5 m layer of reddish-brown sandy clay beneath the sand and gravel. The ground level at the site of the bores was 16.5 m.

P_1 is the only measurable lateglacial raised beach fragment on the south coast of the Firth of Tay in Area A. It is a marked, 50 m-wide shelving step with a surface composition of rounded, fine-medium gravel, and 7 measurements along 150 m of rather gradual back-feature showed an altitude of 17.3–17.9 m.

4. Postglacial raised shorelines and beaches

The Main Postglacial Raised Beach extends for about 4 km north of Leuchars as an extremely flat area of former estuarine mudflats consisting of silty clay, which is brownish near the surface, but bluish-grey lower down, and closely resembles the carse clays of the Earn and the Carse of Gowrie (Chaps.4–6). The old mudflats are encroached upon by the windblown sands of Tentsmuir on the east, and their width between the edge of the dune-sand and that of the lateglacial beach deposits varies from just under to just over 800 m. The old shoreline is very sharply defined, both morphologically and stratigraphically, by the junction of silty clay with lateglacial beach sands. The edge of the latter has been trimmed in places by undercutting of the loose materials by the quiet estuarine waters in which the mudflat deposits accumulated. The carse also penetrates a short distance into some of the deep gullies or dry valleys that dissect the lateglacial beaches, particularly at Craigie and at Vicarsford (Fig.3.3).

Penetration into narrow inlets occurs on a much larger scale southwest of Leuchars. The carse deposits infill the embayment immediately southwest of the village, and extend some distance up the Motray valley. They form a striking terrace with a conspicuous shoreline at Inner Bridge, and extend west from there into a large inlet more than 1½ km long, through which the Moonzie Burn passes into the Motray Water. Within this inlet, they finger into the lower parts of the dry valleys that dissect the sand and gravel deposits near Balmullo (sec.II1d), extending as narrow tongues for several hundred metres up the larger valleys.

Despite their extensive development, stratigraphic information about the carse deposits north of the Eden is scanty. The information available suggests that their thickness is variable and not very great at least in the area north of Leuchars. Augering at a point (NO 4578 2539) about 600 m northeast of Vicarsford proved at least 2.4 m of carse, with a 5 cm layer of fine sand at a depth of 2.1 m, and the carse was seen to be at least as thick in stream-bank sections in the Moonzie inlet. Augering at a point (NO 4605 2408) west of Rhynd, however, showed only 1.4 m of carse clay over fine to medium sand, which could not be penetrated far with the equipment available, and another auger bore 100 m farther east (NO 4612 2408) showed only 0.6 m of carse clay over sand, which could not be penetrated beyond a depth of 2.4 m. A site investigation bore at the same place, however, showed that the sand continues to a depth of 6.1 m (i.e. to about 2.5 m O.D.), where it overlies a 0.6 m-thick bed of peat, which in turn rests on boulders (Lawrie & MacGregor, 1943).

Peat of postglacial age lies at the base of the carse deposits over most of the Earn-Tay carselands (Chaps.4-6). It has also been reported around Wormit Bay (J. Geikie, 1881a), and on the south side of the Eden estuary, beneath carse clay (Walker, 1876; Chisholm, 1962; Armstrong & Chisholm, 1963), and it is sometimes exposed at or near low water mark in these places. Watson (1845) reported fossil oaks in the carse near Leuchars. An Institute of Geological Sciences borehole sunk in 1969 on the floor of a pre-carse valley in St. Michael's Wood (NO 4541 2348) passed through over 1 m of surface peat overlying a 1.2 m-thick wedge of carse deposits, which in turn rest upon a 1½ m-thick layer of peat overlying lateglacial sands. Peat samples from the borehole were radiocarbon dated as follows (Welin, Engstrand, & Vaczy, 1971):

Sample IGS-C14/1	5,830± 110 years B.P.	Base of surface peat
Sample IGS-C14/2	7,605± 130 years B.P.	Top of sub-carse peat
Sample IGS-C14/3	9,945± 160 years B.P.	Base of sub-carse peat

The significance of these dates will be discussed later (Chap. 9).

The Main Postglacial Raised Shoreline was measured at 65 points north of the Eden, and the height data are summarized in Table 3-5.

TABLE 3-5

POSTGLACIAL SHORELINE FRAGMENTS: GUARD BRIDGE TO WORMIT BAY

Location	Altitude (m O.D.)		No. of hts.	Dist. m	Reference numbers
	range	mean			
Main Postglacial Raised Shoreline:					
(Seggie	8.2-8.5	8.4	5	350	A.832-6)
Inner Bridge	7.9-8.4	8.1	5	300	A.827-31
Comerton	7.9-8.4	8.1	4	300	A.135-8
Leuchars-Cast	7.9-8.4	8.2	10	700	A.141-50
Cast-Craigie	8.1-8.5	8.4	15	1,050	A.152-66
Craigie-Vicarsford	8.1-8.9	8.5	12	700	A.173-6,223-30
N. of Vicarsford	8.5-8.7	8.6	7	400	A.231-7
(Greenside Scalp	7.4-8.5	7.9	7	200	A.440-6)
Present-day shoreline (edge of sandflats):					
E. of Lundin Bridge	1.5-1.9	1.7	15	850	A.919-25,927-34

( ) Brackets explained in Text.

The Seggie and Greenside Scalp data should be treated with reserve in the context of overall change in altitude along the shoreline, the former because they were obtained in the narrow Moonzie carse inlet, and are therefore rather high (Chaps.4,6, & 9), and the latter because they were measured on a narrow, rather irregular fragment composed of gravel interbedded with sand. The remaining 53 heights, all on the carse, vary only between 7.9 and 8.9 m in a south-north distance of 5½ km, and the means of each measured stretch show a steady northward increase.

The only lower postglacial raised beach north of the Eden, at Guard Bridge, is almost completely obliterated by a large paper mill.

The present-day shoreline was measured at 15 points along the back of the sandflats east of Lundin Bridge, the altitude varying from 1.5 to 1.9 m in 850 m (Chap.2).

III. STRATHEDEN

The part of Stratheden considered here is the narrow section between Guard Bridge and just west of Cupar (Fig.3.5). It contains abundant fluvioglacial deposits that have been greatly dissected by proglacial streams, gullies, and the River Eden, whose present narrow floodplain is flanked by postglacial river terraces and, in the extreme east, by old estuarine mudflats.

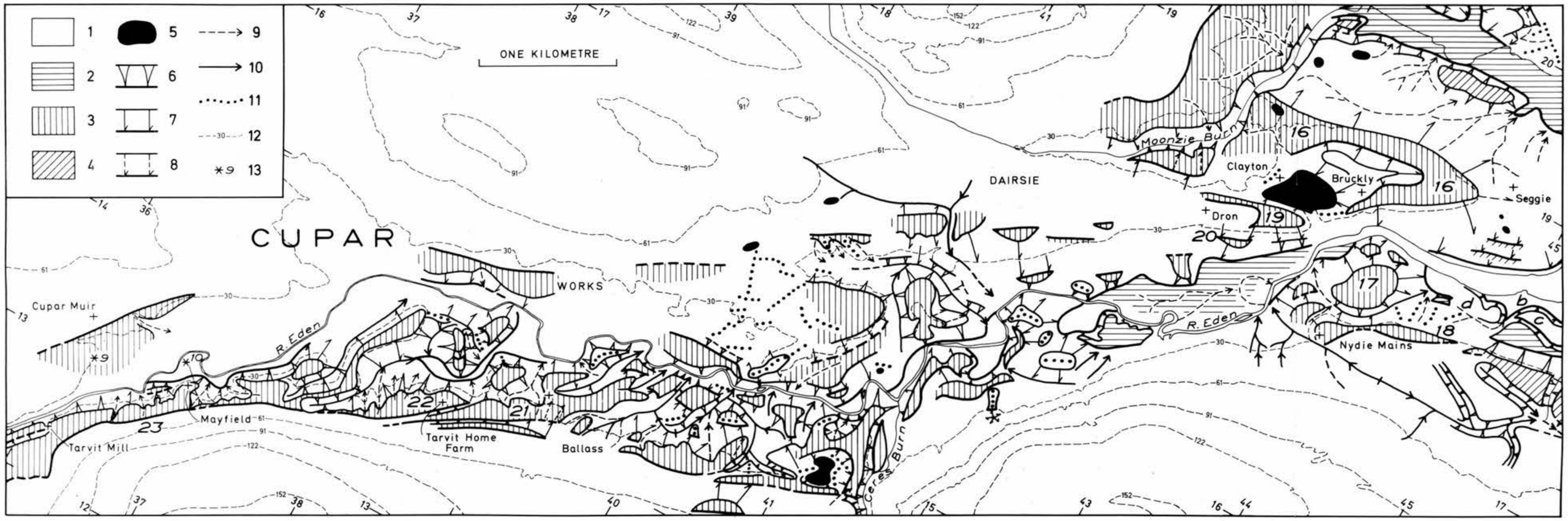

FIGURE 3.5 - Stratheden: Guard Bridge to Tarvit Mill. 1. Postglacial flats (other than 2.); 2. Main carse; 3. Fluvioglacial terrace; 4. Step of uncertain origin; 5. Kettle; 6-8. Steep, moderate, and gentle slopes; 9. Gully or abandoned river channel; 10. Meltwater channel; 11. Ridge of sand & gravel; 12. Contour (m O.D.); 13. Exposure referred to in text.

1. <u>Fluvioglacial features</u>

The fluvioglacial features of Stratheden occur variously as flat terraces, as kettled terraces, and as moundy terrain. The distribution of these forms is shown on the map (Fig.3.5), from which it is clear that even the flattest, most extensive terraces have been severely dissected, probably by both proglacial meltwater streams and by later gullying. Both measurement and the interpretation of its results therefore proved difficult, for fragments of terrace that are sufficiently extensive and well preserved to give meaningful height values are few, and are separated from each other by considerable distances, making correlation difficult (Chap.8). The height data are summarized in Table 3-6 and plotted graphically in Figure 8.5 (Chap.8).

The northeastern end of Stratheden contains lateglacial terraces at 3 distinct levels. The highest level is represented by terrace fragments 16, 18, and 19, the middle level by fragment 17, and the lowest level by 20.

Fragment 16, a conspicuous step fringing a small hill, has a surface composition of sand and subangular to well-rounded gravel with cobbles up to 15 cm in diameter. The altitude of the back-feature, as shown by 19 measurements, declines eastwards from 34.2 m to 32.9 m in a distance of about 600 m along the northern flank of the hill, and from 33.9 to 33.2 m in about 350 m along the southern margin, the gradient in each case being about 2 m/km. Westwards towards the 8 m-deep trench occupied by the Moonzie Burn, the terrace surface becomes irregular and is pitted by a small,

TABLE 3-6

LATEGLACIAL AND POSTGLACIAL TERRACE FRAGMENTS: STRATHEDEN
(in order NE-SW)

Location	Altitude (m O.D.) range	Altitude (m O.D.) mean	No. of hts.	Dist. m	Reference numbers
Fluvioglacial terrace fragments:					
16. Bruckly	32.9-34.2	-	19	900	A.737-55
17. Nydie	25.7-27.4	-	4	250	A.812-5
18. Nydie	33.7-34.9	-	8	400	A.803-8,810,811
19. Dron	35.1-35.3	-	3	150	A.938-40
20. Dron	22.6-22.7	-	3	100	A.941-3
21. Tarvit Home Farm	38.2-40.6	-	7	600	A.841-7
22. Tarvit Home Farm	34.3-35.0	-	3	200	A.848-50
23. Mayfield - Tarvit Mill	38.2-41.9	-	10	1,050	A.756-65
Main Postglacial Raised Shoreline:					
Nydie	8.2- 9.0	8.6	2	50	A.820,821
Dron	7.7- 8.7	8.2	8	850	A.944-51
Lower postglacial terrace fragment:					
d. Nydie	6.1- 6.9	-	7	450	A.817-9,823-6

( ) Brackets explained in Text.

5 m-deep kettle, and it is bounded on the southwest by a large kettle that is now drained through an artificial cut. The gullied, rather gentle northward slope down from the terrace to the Moonzie carse inlet has irregularities that are partly the result of an ice-contact origin, as shown by several small kettles, the meltwaters from which were evidently responsible for some small channels. Fragment 19 is a small step at 35.1-35.3 m (3 heights in 150 m) on the other side of the large kettle from 17.

The narrow terrace fragment 18, across the Eden from 16, lies at a similar altitude and has a similar composition to the latter, but exhibits a somewhat steeper gradient, the altitude declining eastwards from 34.9 m to 33.7 m in 400 m at about 3 m/km.

Fragment 17 is a flattish plateau that is separated from 18 by a large dry channel, and slopes northeastwards from 27.4 m to 25.7 m in 250 m (4 heights). Fragment 20 is a small, narrow step at 22.6-22.7 m (3 heights in 100 m).

All 3 fluvioglacial terrace levels are represented by other features east of Dairsie, none of which were measurable. The highest level clearly postdates fragment 8 (sec.I4, Fig.3.2), the western (highest) end of which, some 1½ km to the east, is at least as high as the eastern (lowest) end of 18, and it is evident that it was formed in the close proximity of wasting glacier ice, as shown by the kettles, and by the kames at a much lower level that almost choke the floor of the valley southeast of Dairsie (Fig.3.5). It is likely, therefore, that terrace fragments 16/19 and 18 are the remnants of an outwash train associated with a wasting ice-margin between Dairsie and Nydie, and that they have no correlatives farther upvalley, except possibly for kame terraces that might occur amongst the small, unmeasurable terrace fragments.

The middle and lowest terraces almost certainly have upvalley correlatives, however (see Chap.8, Fig.8.5): the former is possibly contemporaneous with flattish spreads that are separated from each other by large dry channels, kettles, and dead-ice hollows near the confluence of the Eden and the Ceres Burn (Fig.3.5). An Ordnance Survey bench mark on one of these flattish spreads indicates a ground level of 34.4 m at NO 4081 1592. North of the Eden, these flattish areas are replaced westwards by a kame-complex, in which the surface material is coarse sand and gravel with a liberal scattering of coarse angular blocks. South of the Eden, however, this middle terrace level is continued by terrace fragment 21, part of an area of long fingers of terrace isolated from each other by large dry channels. The measurable part of 21 slopes down northeastwards from 40.6 m to 38.2 m in 600 m (7 heights), a gradient of about 4 m/km. A narrow terrace, too vague to measure, occurs upslope of 21, both features being cut away westwards by terrace 22, which is morphologically continuous with 23, the highest terrace for some distance southwest of Cupar. The combined feature (22-23), which is probably contemporaneous with the lowest terrace (20) down-valley (Chap.8), is dissected by large channels and gullies, and has a composition that is somewhat finer than that of the highest terraces farther east, consisting of medium well-stratified sand with occasional gravel. This material, which was proved in sections to a depth of at least 3 m, coarsens slightly upvalley. The whole feature slopes downvalley from 41.9 m to 34.3 m in 2.8 km, a gradient of about $2\frac{3}{4}$ m/km. Just beyond the upvalley limit of mapping, the terrace surface becomes markedly uneven, and passes eventually into moundy terrain.

The fluvioglacial features of Stratheden thus represent successive outwash terraces formed in association with a southwestward-receding ice margin. Their relationship to shoreline displacement will be considered later (Chap.8).

2. Postglacial raised shorelines and river terraces

At the extreme northeastern end of Stratheden the postglacial raised estuarine flats previously described in the Guard Bridge area (sec.I1) continue a short distance upvalley. The main carse level occurs as a tiny remnant at Nydie and a much more extensive terrace at Dron, the former lying at 8.2-9.0 m (2 heights in 50 m), and the latter at 7.7-8.7 m (8 heights in 850 m). The Dron feature is somewhat dissected by former courses of the Eden, and the height values are almost certainly depressed in consequence.

In a staircase between postglacial raised beach fragment b (sec.I1) and the Nydie main carse remnant is postglacial terrace d, which has a sharp back-feature at its western end, but a channel at the back farther east. 7 heights on the terrace flat decline eastwards from 6.9 m to 6.1 m in 450 m. Fragment d is probably a fluvial contemporary of fragment c (sec.I1).

Narrow fluvial terrace remnants of postglacial age flank the Eden intermittently along its course, but only near Cupar do they achieve any great extent. Downvalley from Cupar the Eden is frequently engorged through fluvioglacial assemblages, and between bedrock walls in places.

3. <u>The lateglacial marine clay of Stratheden and the Eden estuary</u>

At Cupar Muir there are some disused claypits (*9, Fig.3.5) in which is exposed a dark reddish-brown, laminated, sandy silty clay, which is overlain by sand and gravel both at Cupar Muir and in a section at Mayfield (*10, Fig.3.5). In the latter exposure a 50 cm-layer of the clay rests on fine-medium sand, and is overlain by at least 3 or 4 m of the sand and fine gravel of which terrace fragment 23 is composed. According to D. Page (1859), the clay at Cupar Muir is 4½-6 m thick, and rests on till.

Both in its physical character and in its occurrence beneath sandy lateglacial deposits, the clay at Cupar Muir and Mayfield is similar to that found widely around the Eden estuary (secs.I5, II1c, & II3). It has also been recorded beneath sand and gravel in former claypits at Seggie (NO 4495 1885) and at Ballass (NO 3875 1440), as noted by A. Geikie (1902).

The altitude of the top of the clay is 14.0-15.4 m in St. Andrews (*1, Fig.3.2), 13.4-16.3 m at the North Haugh (sec.I2), 13.4 m at Leuchars (*4, Fig.3.3), and about 27-30 m at Cupar Muir and Mayfield. The recorded thickness varies greatly, from 0.5 m at Mayfield and beneath terrace 9 (*5, Fig.3.3), to 13.8 m in St. Andrews.

Several faunal remains have been recorded in the clay, both in Stratheden and around the Eden estuary, including the following: shells, principally of the starfish Ophiolepis gracilis; skeletons of arctic seals, probably Phoca hispida; skeletons of surf and eider ducks, Oidema and Somateria; and whale-bones (D. Page, 1859, 1860; R. Walker, 1863, 1864, 1876; W. Turner, 1870; A. Geikie, 1902). From these remains, together with the scattered smoothed and striated stones, including material from the Ochils, the Sidlaws, and the Highlands, the arctic marine character of the laminated clays cannot be disputed.

In view of the widespread occurrence of the clay, and the fact that it is always found beneath fluvioglacial material, except for occurrences in St. Andrews and at Leuchars where it is also found beneath lateglacial beach deposits, it seems reasonable to regard it as one, contemporaneous deposit that preceded the later phases of outwash deposition as represented by terrace 5 (Fig.3.2) and all subsequent fluvioglacial terraces . If this is true, a readvance of the ice is indicated, for with the exception of the most recent terrace (22-23), the successive fluvioglacial terraces beneath which it occurs are each associated with a former ice-margin position that lies well to the east of the western limit of the clay. However, there is no evidence that the clay is anywhere overlain by till. This matter is discussed further in Chapter 8.

CHAPTER FOUR

AREA B - WORMIT BAY TO BRIDGE OF EARN

Introduction

Area B extends from the western end of Wormit Bay (National Grid easting NO 385) to a north-south line (NO 10) passing through the farm of Freeland, 3 km west of Bridge of Earn, an east-west distance of 28.5 km. It includes the south shore of the Firth of Tay from Wormit Bay to the confluence of the rivers Earn and Tay, and the broad lowland on both sides of the tidal portion of the River Earn (Fig.1.2).

The relief is dominated by the steep northern slopes of the Ochil Hills, which reach down to the water's edge over much of the stretch between Wormit Bay and Newburgh. West of Newburgh the area of drift-covered lowland increases, and the sinuous tidal portion of the River Earn flows through an expanse of raised estuarine flats, 3-4 km wide, backed by the Ochils to the south and by the steep, and in places precipitous, slopes of Moncreiffe Hill to the north.

The evidence in Area B of former shorelines and beaches and related fluvial and fluvioglacial features is discussed for convenience in two sections:

I. The narrow coastal fringe between Wormit Bay and Newburgh (Figs.4.1 & 4.2).

II. The Newburgh-Bridge of Earn area (Fig.4.3).

I. WORMIT BAY TO NEWBURGH

Along this stretch of coast steep slopes of Old Red lavas patchily mantled with till descend unbroken, except where interrupted by the presence of steps, to the present-day shore. These slopes generally steepen considerably below altitudes of 30-45 m O.D. and steps of any sort are rare, those that do occur being often the expression of outcropping lava beds. Depositional terraces are well developed only to the west of Flisk Point, and even there they do not attain the extent and high degree of preservation of those to the west of Newburgh (sec. II). There are occasional large meltwater channels between Wormit Bay and Flisk Point.

1. Wormit Bay to Flisk Point

Chambers (1848) postulated a marine origin for rock benches that occur up to considerable altitudes along the northern slopes of the Ochils, particularly between Tayport (in Area A) and Balmerino. On Spears Hill, just west of Tayport, for example (Fig.3.3), he reported such features at 34, 46, 61, 73, and 82 m above sea level, but as A. Geikie (1902) pointed out, they are really the morphological expression of successive sheets of andesite. Two flat, 50 m-wide benches in which rock is exposed occur on the northern slopes of Scurr Hill (Fig.4.1), at altitudes of somewhat greater than 45 m and about 15 m O.D. respectively, and other rock benches occur near Kirkton and east of Thornton. The absence of any marine deposits or definite subaerial detritus and the occasional presence of a thin smear of till on the bench surfaces,

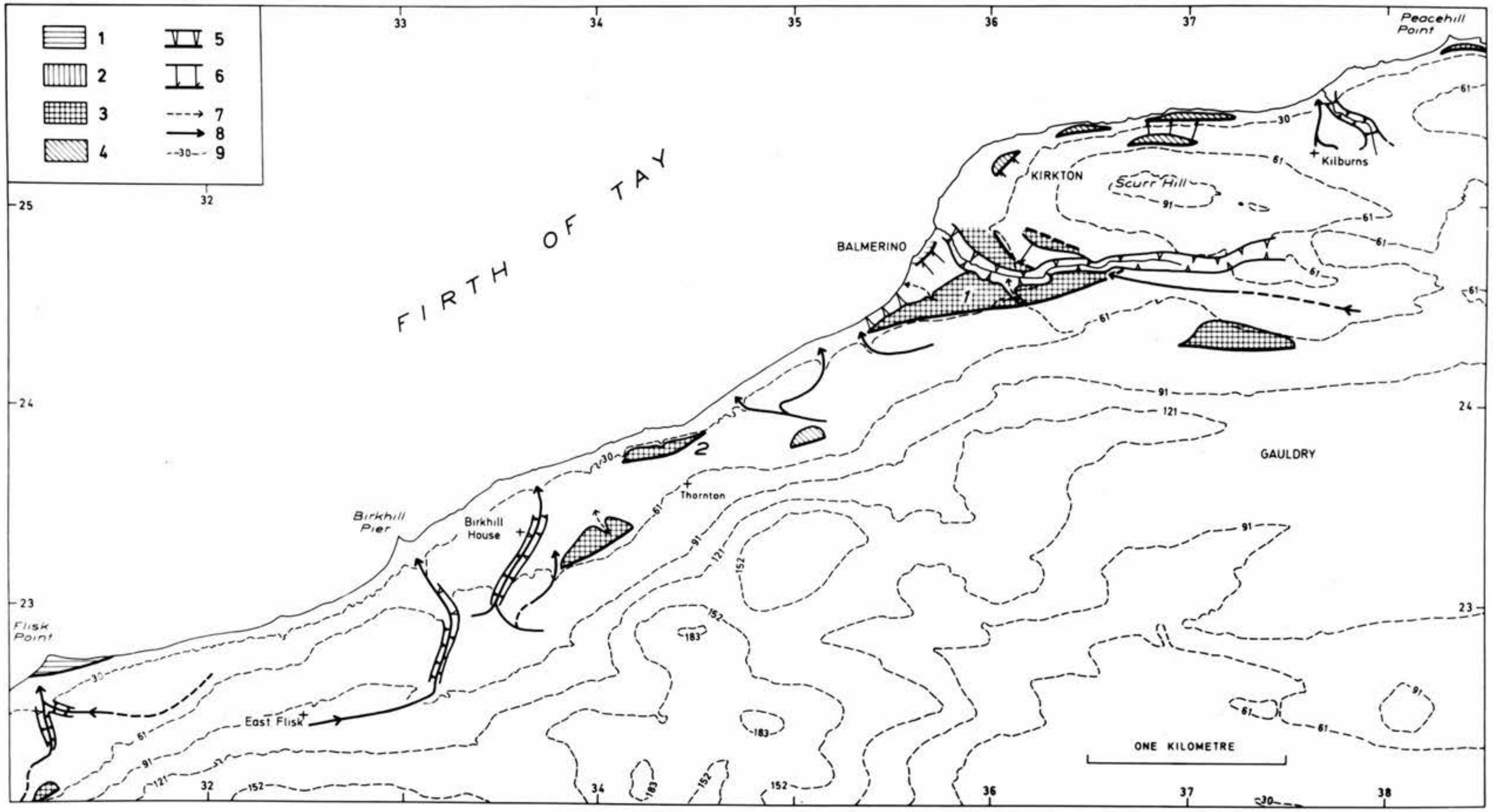

FIGURE 4.1 - Wormit Bay to Flisk Point. 1. Postglacial raised beach; 2. Lateglacial raised beach; 3. Fluvioglacial terrace; 4. Rock bench; 5. Steep slope; 6. Moderate or gentle slope; 7. Gully; 8. Meltwater channel (broken line where vague); 9. Contour (m O.D.).

together with the abundant evidence of glacial moulding and plucking in the hills of northern Fife generally, including drumlinoid, crag-and-tail, and roche moutonnée forms, all strongly suggest that the rock benches are largely the result of selective glacial erosion of the lava beds.

Occasional terraces of probable depositional origin do occur, however. Near Peacehill Point is a narrow terrace with a maximal width of about 25 m and a rear break of slope that is insufficiently distinct for accurate measurement. An Ordnance Survey contour on the terrace surface suggests an altitude of approximately 23 m O.D. A section about 2 m below the top of the very steep bluff fronting the terrace revealed a mass of very angular cobbles, of uniform lithology. The origin of the terrace is uncertain, but there is nothing to suggest a marine origin.

Terrace 1 (Fig.4.1) which was noted by Chambers (1848), has a surface composition of coarse, subangular to well rounded gravel, with stones up to about 13 cm in diameter. It is triangular in plan and lies at the western end of a large steep-sided valley, with walls up to 12 m high, situated within a broader valley or depression, the floor of which extends eastwards to a col separating it from the Wormit Gap (Chap.3). The form of the steep-sided valley suggests that it may have originated as a meltwater channel. The stream now occupying it traverses the gravel terrace through a 5-6 m-deep gorge down to the shore at Balmerino.

Despite the fact that the terrace surface shelves quite steeply away from the back-feature, the latter is sharp, and 7 measurements along the seaward end of the southern break of slope show that it slopes steeply along its length from east to west, from 27.2 to 22.3 m O.D. in a distance of 300 m, equivalent to a gradient of 16 m/km (Table 4-1). Such a gradient precludes a marine origin and, in conjunction with the form and composition of the feature, suggests that it is a fan of fluvioglacial origin deposited in relation to a relative base level well above the present. The fan is very unusual amongst presumed fluvioglacial features in this area, however, in that it slopes down from east to west, and was clearly deposited by water flowing in this direction, against the regional trend of both direction of ice movement and direction of meltwater flow.

The only other terrace between Wormit Bay and Flisk that is both depositional and measurable is fragment 2 (Fig.4.1, Table 4-1), a narrow, 50 to 60 m-wide terrace, about 300 m long, at the top of a steep cliff. Its altitude was shown by 7 measurements to be 35.7-36.1 m O.D., and a small exposure at the front of the terrace revealed closely packed, size sorted, sub-to well rounded gravel and cobbles. Its origin is not clear because neither the height evidence on the rather gradual back-feature nor the composition is conclusive, but since there is no evidence in the area of a former shoreline at this altitude, and since fragment 1, of presumed fluvioglacial origin, is at a much lower altitude and only 1.2 km away, it is considered likely that the feature is of fluvioglacial rather than marine origin.

A possible depositional terrace at Birkhill, at about 55 m O.D. (O.S. bench-mark), was not measurable, but the fact that probable meltwater channels pass downslope of it and close to it suggests a

TABLE 4-1

LATEGLACIAL TERRACE FRAGMENTS: WORMIT BAY TO NEWBURGH

Location	Altitude (m O.D.)		No. of hts.	Dist. m	Reference numbers
	range	mean			
Lateglacial raised shoreline fragments (in order E-W):					
(A. Durward's Scalp	20.0-20.2	20.1	2	50	B.59,60)
B. Logie	20.5-21.6	21.1	9	300	B.44-8,67-70
C. Ca[illegible]ase - Ballinbreich	21.2-22.2	21.6	14	1,000	B.14-27
D. Logie - Ballinbreich	26.3-28.3	27.3	14	1,050	B.30-35,37-41,43, 93,94
Fluvioglacial terraces (in order E-W):					
1. Balmerino	22.3-27.2	-	7	300	B.695-701
2. Thornton	35.7-36.1	-	7	250	B.702-8
3. Ballinbreich	28.5-33.5	-	11	800	B.3-5,11-13,88-92

( ) Brackets explained in text.

fluvioglacial origin.

The channels near Birkhill and East Flisk are impressive features between 6 and 12 m deep, cut in rock, with sheer sides in places, and following courses that are markedly oblique to the general trend of the contours before plunging steeply downslope. These characteristics suggest that they are marginal and/or submarginal meltwater channels passing into subglacial chutes at their lower ends.

Between Birkhill Pier and Flisk Point steep slopes descend unbroken to the present shore from altitudes greater than 45 m O.D., and terraces are absent except for a small raised beach fragment at Flisk Point. This feature is densely vegetated so that accurate measurement was impossible, but it is distinctly lower than the 7.6 m contour, and is clearly much lower than the Main Postglacial shoreline would be if it existed at this point. A. Geikie (1902) referred to both this fragment and an extremely vague feature at Balmerino as parts of the "25-feet beach".

2. Flisk Point to Newburgh

West of Flisk Point the scene changes, and the steep slope of the Ochils is separated from the Tay by a terraced area up to 500 m wide, containing evidence of both lateglacial and postglacial raised shorelines.

a) Lateglacial shorelines and fluvioglacial features

Between Balhelvie and Ballinbreich two major lateglacial terraces with a surface composition of sand and gravel extend over relatively great distances. The higher terrace (D & 3, Fig.4.2), 2.4 km long

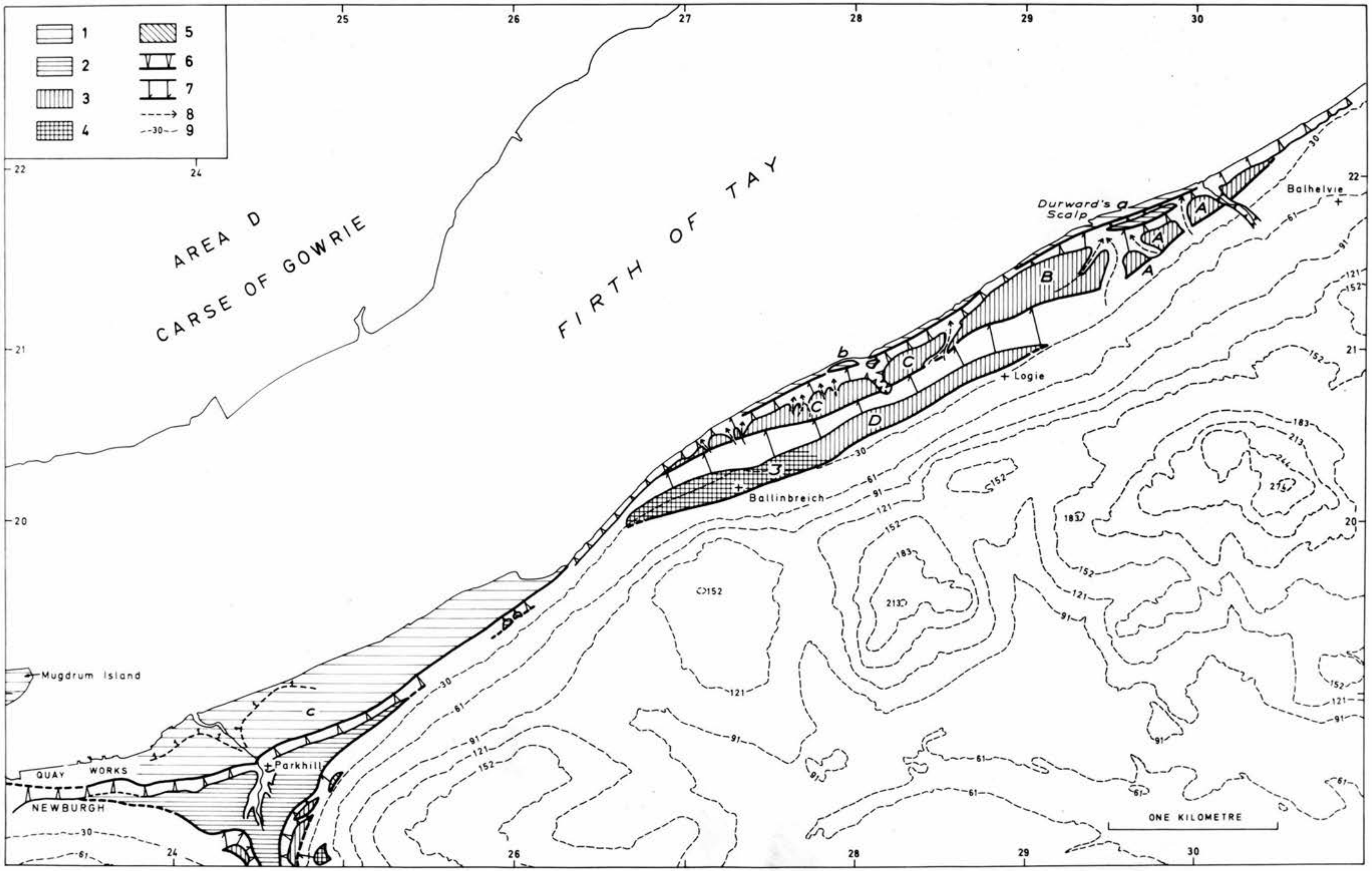

FIGURE 4.2 - Flisk Point to Newburgh. 1. Lower postglacial flat; 2. Main carse; 3. Lateglacial raised beach; 4. Fluvioglacial terrace; 5. Step of unknown origin; 6. Steep slope; 7. Moderate or gentle slope; 8. Gully; 9. Contour (m O.D.).

and 100–150 m wide, has a fairly flat surface that shelves seawards considerably, and at each end it becomes lost in fairly gentle slopes descending from the well defined upper limit of sand and gravel at 45–50 m O.D. The measurements obtained on the moderately sharp back-feature show a slope from 33.3–33.5 m at the western end to 26.3–27.1 m at the eastern end, equivalent to an overall gradient of about 3.3 m/km. This would seem to suggest a fluvioglacial origin, but the gradient is not constant along the whole feature, the gradient of the western part of the terrace (3, Fig.4.2, Table 4-1) being 5.8 m/km, but on the eastern part (D) only 1.2 m/km. The eastern part, which lies at 26.3–28.3 m as shown by 14 measurements over a distance of 1,050 m (D, Table 4-1), must be considered as of possible marine or glaciomarine origin, although the complete absence of lateglacial shoreline features farther east in Area B means that no supporting evidence can be cited.

The lower terrace, which extends for 3.6 km and comprises raised beach fragments A,B, and C (Fig.4.2), varies in width from 30 to 250 m, and is flatter, shelves less steeply, and has a much sharper back-feature than the higher terrace. It is dissected by numerous gullies, some of which start on the backslope, and at the eastern end the beach has been reduced to three small, isolated fragments collectively referred to as A (Fig.4.2, Table 4-1), separated from each other and from fragment B by large bowl-like depressions. Fragments B and C are likewise separated from each other by a large gully. The 25 altitude measurements along the shoreline of A,B, and C range between 20.0 and 22.2 m in 3.3 km, part of the range of 2.2 m being accounted for by local variations caused by the proximity of gullies and by other irregularities, and part by an overall slope along the shoreline, which is higher in the west (C) than in the east (A). It is almost certain that the altitude values for fragment A have been depressed by the intense gullying, so the data have been enclosed within brackets in Table 4-1.

The only other signs of lateglacial terraces between Flisk Point and Newburgh are a few small degraded fragments in the Parkhill area (Fig.4.2).

b) Postglacial raised shorelines

The only fragment of the Main Postglacial beach and shoreline that is measurable east of Ballinbreich is a narrow terrace of carse clay, 400 m long and 30 m wide, at Durward's Scalp. Its surface is very flat, and 7 measurements along the excellent shoreline feature range between 8.8 and 9.2 m O.D. (Table 4-2). Farther west this terrace is represented by a marked convexity in the steep bluff fronting lateglacial fragments B and C.

West of Ballinbreich the carse is absent for 1½ km owing to the presence of cliffs, after which tiny fragments of carse terrace occur along a concave break of slope which, towards Parkhill, becomes a sharp feature backing a terrace of increasing width. This terrace broadens into a triangular feature, described by Buist (1841, p.34) as of "the richest of the carse-clay", infilling the lower part of the Lindores valley (Fig.4.2). The western part of this carse fragment is obscured by the buildings of Newburgh, but the eastern part, at Parkhill, was measured at 9 points in a 450 m stretch, at 9.1-9.9 m

TABLE 4-2

POSTGLACIAL RAISED SHORELINE FRAGMENTS: WORMIT BAY TO NEWBURGH

Location	Altitude (m O.D.)		No. of hts.	Dist. m	Reference Numbers
	range	mean			
The Main Postglacial Raised Shoreline:					
Durward's Scalp	8.8-9.2	9.1	7	300	B.76-82
Parkhill	9.1-9.9	9.5	9	450	B.303-9,312,313
Lower postglacial raised shoreline fragments:					
(a. Durward's Scalp	3.0-3.2	3.0	4	150	B.84-7)
b. Ca[illegible]ase	3.8-4.0	3.9	6	150	B.49-54
c. Parkhill	3.2-3.5	3.3	13	850	B.709-21

( ) Brackets explained in text.

O.D. (Table 4-2). The altitude rises slightly towards the apex of the triangle, suggesting, together with an increasing number of stones in the carse soil in the same direction, a fan-like influence of the Pow of Lindores, old courses of which are evident on the carse surface near the apex.

Postglacial terraces lower than the Main Postglacial level occur at 3 places. Fragments a and b are at the base of a steep bank, and measurement was not easy because the narrowness of the terraces left little room for the avoidance of material that has accumulated at the foot of the backslope. Fragment a was particularly difficult in this respect. The altitudes of a and b are 3.0-3.2 m (4 measurements in 150 m) and 3.8-4.0 m (6 measurements in 150 m) respectively (Table 4-2). Fragment c is much more extensive, being 3.3 km long and up to 350 m wide. It is backed by a very steep 4-5 m-high bluff separating it from the Parkhill carse. Owing to human interference west of the stream crossing the terrace, the shoreline was measured only to the east, where 13 measurements in 850 m ranged between 3.2 and 3.5 m O.D. (Table 4-2). The low altitude of fragments a,b, and c raises the question of whether they are raised beaches or merely reclaimed land, a matter that will be dealt with in a wider context later (Chap.9). For the present it will suffice to say that an even lower level intervenes between terrace c and the protective dyke that lines the foreshore east of Newburgh, and that land that is known to have been reclaimed, both on the north side of the Tay (Chap.6) and on Mugdrum Island, lies at altitudes of 2.1 m or less. It is therefore concluded that fragments a,b, and c are raised beaches.

The two postglacial raised shorelines at Parkhill were the only ones measured by Donner (1963) in the Tay basin. He obtained altitudes of 10.5 m and 3.5 m respectively for the Main Postglacial and fragment c shorelines, which in view of his method of measurement seem to agree remarkably well with the writer's measurements. Unfortunately he did not specify what datum he used, for neither the barnacle line nor the upper limit of Fucus is present near Parkhill, so the close agreement may be fortuitous (Chap.2).

II. THE NEWBURGH-BRIDGE OF EARN AREA

West of Newburgh (Fig.4.3) evidence of former beaches and shorelines is prolific, and great expanses of raised estuarine flats contrast vividly with the bold and often precipitous bounding hillslopes. The tidal portion of the River Earn follows a markedly sinuous course through the tract of estuarine deposits, and numerous riverbank sections provide valuable stratigraphic information. The most extensive and most distinctive element in these flats is the carse, with which the following account therefore begins.

1. The carselands

In its broader Scots usage the term 'carse' denotes an alluvial flat or river floodplain, but from an early time it has also been more specifically applied to the clay flat-lands now known to be composed of postglacial estuarine deposits. It is not known how early this more specific usage entered the literature, but it was employed

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FIGURE 4.3 - The Newburgh - Bridge of Earn area. 1. Lower postglacial flat; 2. Main carse; 3. Lateglacial raised beach; 4. Fluvioglacial terrace; 5. Step of unknown origin; 6. Alluvial fan; 7. Closed depression; 8. Alluvium; 9. Riverbank exposure of carseland stratigraphy; 10-12. Steep, moderate, and gentle slopes; 13. Gully; 14. Linear depression; 15. Meltwater channel; 16. Sharp-crested ridge of sand & gravel; 17. Rounded-crested ridge of sand & gravel; 18. Contour (m O.D.); 19. Riverbank exposure studied in detail; 20. Line of bores. The numbered dots are positions of site investigation bores.

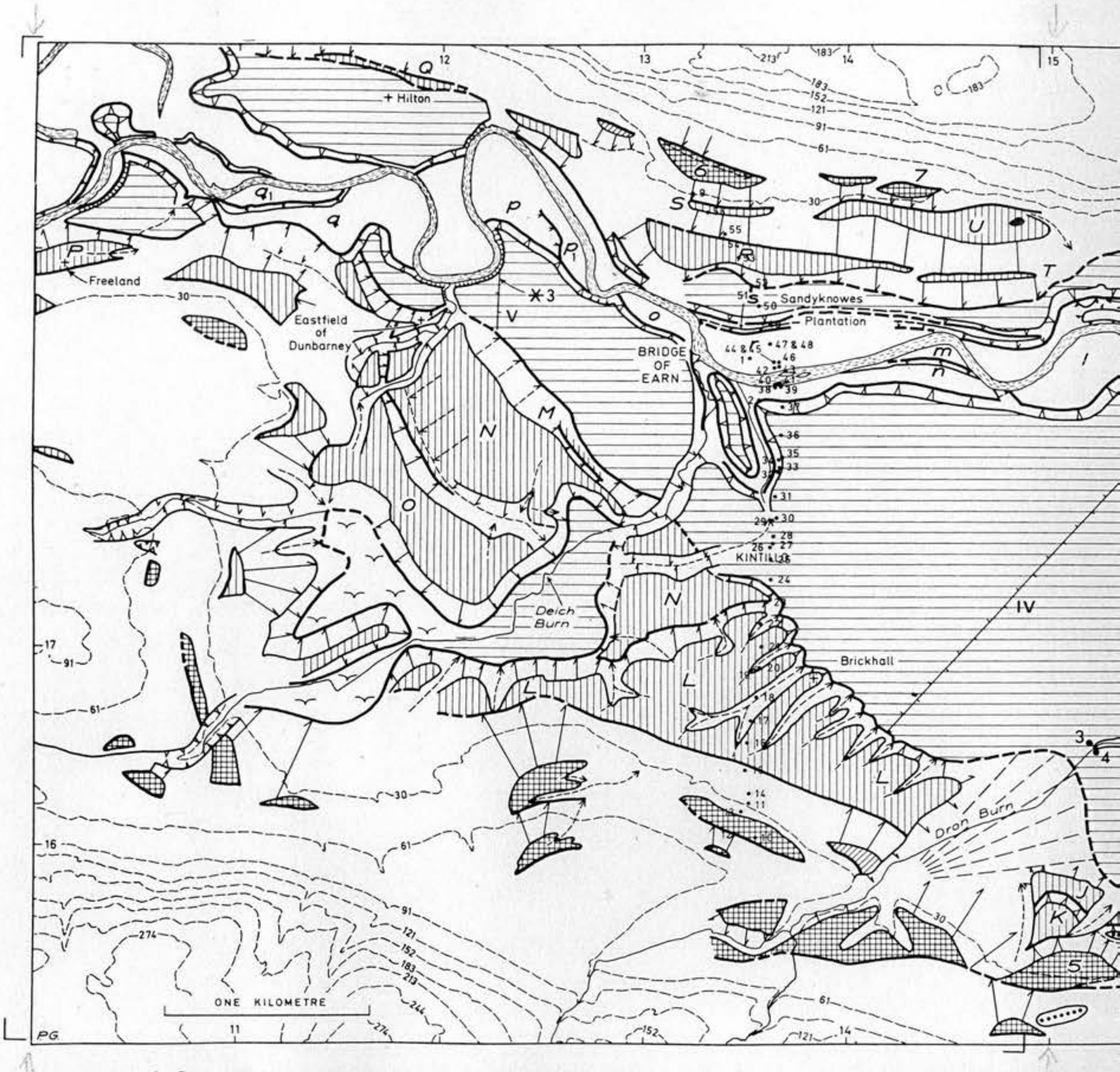


FIGURE 4.3 - The Newburgh - Bridge of Earn area. 1. Lower postglacial fl
6. Alluvial fan; 7. Closed depression; 8. Alluvium; 9. Riverbank exposur
ion; 15. Meltwater channel; 16. Sharp-crested ridge of sand & gravel; 17
detail; 20. Line of bores. The numbered dots are positions of site inves

POSITIONS OF SITE INVESTIGATION BORES

by Buist (1841), Chambers (1848), A. Geikie (1861,1862), Jamieson (1865), and by almost all subsequent students of sea-level changes in Scotland. It is also employed throughout this thesis, but it must be made clear that the use of the word 'Carse' in place-names is much broader; the Carse of Gowrie, for example, contains large tracts in which lateglacial sandy and clayey materials, very different from the carse deposits, lie at the surface (Chap.6).

The limits of the carse deposits are, in most cases, readily identified both stratigraphically and morphologically. In addition to the Newburgh-Bridge of Earn area, carselands occur around and north of the Eden estuary (Chap.3); between Flisk Point and Newburgh (sec.I2b); up the Earn and Tay valleys as far as Kildinny and Sherifftown respectively (Chap.5); and extensively in the Carse of Gowrie (Chap.6).

a) The nature and origin of the carse deposits

Carse clay was described by Buist (1841, p.31) as "a rich aqueous deposite, consisting of finely comminuted particles of siliceous and argillaceous matter, the latter greatly predominating, commingled with rich putrescent vegetable remains", and by F.Smith (1874, p.269) as "a slightly indurated clay, with a conchoidal fracture" and without stratification. The writer's observations, based on numerous sections and boreholes, agree with these descriptions. The carse consists of silty clay and clayey silt, and is tenacious and difficult to penetrate near the surface, where it forms a 'carse crust' 1.0-1.5 m thick and brown or yellowish-brown in colour, but soft and easy to penetrate lower down, where it forms a water saturated blue-grey 'sleech'. Plant remains, chiefly of reeds, are common throughout the deposit, and they often give rise to an unpleasant fetid smell. There is in general no distinct stratification except occasionally near the base, and stones are absent except for occasional ones near the inner edge of the carselands. There are occasional thin layers and lenses of sand, as noted by Buist (1841).

The above comments serve as a general description of the carse in the whole of the Earn-Tay basin and in north-east Fife. There are slight local facies variations, but in general these are of lesser magnitude than the differences between the carse and all other deposits, so that the carse is distinctive and readily identified in the field. Only in a restricted area in the Carse of Gowrie was any difficulty experienced in distinguishing the carse from other materials (Chap.6).

The carse has been regarded as an estuarine deposit by almost all workers at least since the 1790's (Sinclair, 1791-8). Both Buist (1841) and Jamieson (1865) likened it to the muds now accumulating in the Tay estuary, and Jamieson also stated that the carse and the underlying peat are of postglacial age. J. Geikie (1881 a, c, d; 1894), however, whilst not disputing its estuarine origin, denied its similarity to the present estuarine muds and likened it instead to "those laminated clays of true glacial age which contain Arctic shells" (1881a, p.397), and to "that fine silt or clay which results from the grinding action of glaciers" (1881d p.34). Geikie agreed with the stratigraphic position of the carse as stated by Buist and Jamieson, and as generally confirmed by later work (sec.II1e), and with the floral evidence in the sub-carse peat and faunal evidence in the carse that indicate temperate conditions, but he correlated part of the carse deposition with a readvance of valley glaciers in the Highlands. This view found little support from either contemporary or later workers, and is clearly refuted by other evidence (Chap.9). It will be noted shortly (sec.II1c) that Geikie sometimes failed to differentiate the carse from older marine formations, which may explain his unorthodox views.

There have been at least two dissenters from the general view that the carse is of estuarine origin. Fleming (1825) favoured a lacustrine origin, and ascribed the faunal remains to a later marine inundation. T.Brown (1870) regarded the Earn carselands as being of fluviatile origin, his chief reason being the absence of marine fossils, and he ascribed the Earn terraces (including the carse) to the action of floods rather than to base-level changes.

No marine shells or other faunal remains have been recorded in the carse deposits of the Newburgh-Bridge of Earn area, nor were any discovered by the writer. However, marine shells are abundant in the carse farther east, in the Carse of Gowrie (Chap.6), and in the Forth carselands, where the remains of several stranded whales have been discovered (Chap.9).

b) <u>Surface form and extent</u>

The carselands of the Newburgh-Bridge of Earn area (Fig.4.3) cover an area of about 18 sq.km and occur widely both north and south of the River Earn. They extend for 10 km in a west-east direction and have a maximal breadth of 3 km.

The first and most striking visual impression of the carse surface is of great flatness over extensive areas. The occasional minor irregularities rarely exceed 0.3 m in amplitude, and are usually discernible only because of increased dampness in the slight depressions. Locally, however, the carselands are sharply interrupted by valleys containing streams emanating from higher ground, including the 100 to 150 m-wide trench of the River Farg, the smaller valleys occupied by Carey Stank and the Dron and Deich Burns, and the steep-sided trench of the Earn itself. The Earn trench, which varies between 400 m and 800 m in width and is much less sinuous than the river itself, is bounded by 6 m-high walls, and contains low terraces that are above the present tidal floodplain of the Earn but well below the main carse level. These terraces are morphologically very distinct, with flat surfaces, very sharp breaks of slope, and steep bluffs to front and rear, but being confined within a trench occupied by a meandering river they are both narrow and fragmented. East of Bridge of Earn their composition is not unlike that of the main carse deposits, being perhaps slightly coarser, and their origin is similar (sec.II1d & Chap.9), but to the west they become increasingly sandy and cannot be classified as carse deposits, although they are dealt with under the carseland heading for convenience.

Almost everywhere, the main carse is separated from the sandy lateglacial raised beaches by a low but clear bluff, the main exception being where the Farg and Dron alluvial fans make precise morphological delimitation difficult (Fig.4.3). The outer edge of the large Farg fan appears to merge imperceptibly with the carse surface, although the change in surface material from sand and gravel to stoneless clay is abrupt. The junction with the carse of the much smaller, more gently sloping Dron fan is even less easy to demarcate.

c) Altitudinal data : the main carse level

Previous statements about the altitude of the main carse level have been very misleading, either because of extreme approximation (e.g. Jamieson, 1865; F. Smith, 1874), or because of a failure to differentiate between the carse and older, lateglacial formations. The accounts of J. Geikie (1881a, 1894) suffer from both short-comings. Having correctly stated (1881a, p.394) that a substantial part of the Earn carse flats does not exceed an altitude of 32 feet (9.8 m), he went on to claim, incorrectly, that the "upper margin of the Earn flats is ... approximately horizontal, and continues at an elevation of 45 feet as far inland as Dalreoch ..." This misconception arose from a failure to recognize the distinct bluff separating the carse from higher features of sandy composition.

The back of the main carse, the Main Postglacial Raised Shoreline, was measured at 122 points in the Newburgh-Bridge of Earn area, and the data are summarized in Table 4-3 , from which it is evident that the shoreline rises gently in altitude from 9.5-9.8 m near Carpow in the east to 10.2-10.9 m at Freeland in the west, an east-west distance of 10 km. The measurements at 3 locations, indicated by brackets in the table, must be treated cautiously in the context of overall change in altitude along the shoreline. The 3 Nethy Burn measurements were obtained on a small carse

TABLE 4-3

THE MAIN POSTGLACIAL RAISED SHORELINE: THE NEWBURGH - BRIDGE OF EARN AREA

Location	Altitude (m O.D.)		No. of hts.	Dist. m	Reference numbers	
	range	mean				
South of the River Earn (in order E-W):						
Ferryfield of Carpow	9.5-9.8	9.7	8	350	B.671-3,678-82	
(Nethy Burn	9.3-9.5	9.4	3	150	B.741-3	)
Cordon	9.7-10.0	9.8	10	450	B.683,684,687-94	
(Netherton	9.4-9.8	9.6	6	350	B.223,225-9	)
Dron Burn - Brickhall	9.9-10.5	10.2	14	700	B.128-37,151-4	
Brickhall - Kintillo	9.9-10.3	10.1	10	500	B.118-27	
(Deich Burn	10.3-11.1	10.8	10	400	B.169-78	)
Bridge of Earn	10.1-10.6	10.4	16	800	B.95-106,113-6	
Eastfield of Dunbarney	9.6-10.0	9.8	6	250	B.252-7	
Freeland	10.2-10.9	10.6	8	550	B.278,279,282-7	
North of the River Earn (in order from W-E):						
Hilton	10.4-10.5	10.5	3	150	B.405-7	
Sandyknowes Plantation	10.2-10.4	10.3	5	350	B.461-5	
Mains of Kinmonth	9.9-10.3	10.1	7	400	B.290-2,324-7	
Muirton - Muirhead	9.9-10.5	10.2	16	1,200	B.315,331-6,339-41, 343,344,348-51	

( ) Brackets explained in text

remnant between the Nethy Burn and a gully; the 6 measurements at Netherton are almost certainly affected by a broad depression along the old shoreline; and the 10 Deich Burn readings were obtained in a narrow carse inlet (Chaps.6 & 9). The means of the remaining 7 sets of measurements south of the Earn, from east to west, are: 9.7 m, 9.8 m, 10.2 m, 10.1 m, 10.4 m, 9.8 m, 10.5 m. The set of measurements at Eastfield of Dunbarney is anomalous in terms of the westward increase in altitude, being about 0.6 m too low at 9.8 m. There is no obvious explanation for this anomaly (but see sec.II1d).

The eastward decline in altitude along the Main Postglacial Raised Shoreline is also evident north of the Earn, where the means of 4 groups of measurements, in order from west to east, are: 10.5 m, 10.3 m, 10.1 m, 10.2 m, The latter value (Muirton-Muirhead) seems a little high in comparison with the rest of the shoreline, possibly because the carse is very thin in the shoreline area, and overlies a somewhat irregular surface (sec.II1e). Obvious protrusions of sandy material from beneath were avoided during measurement, and a few measurements obtained on minor rises subsequently found to be sand outcrops have been omitted from the data in Table 4-3, but it is nevertheless possible that a few similar cases remain undetected. Apart from this, the question of a possible relationship between depth of carse and surface altitude will be considered later (Chap.9).

An outstanding characteristic of the data is the consistency of the shoreline measurements. Of the 14 groups of measurements, 4 groups (totalling 48 measurements) have an altitude range greater than 0.5 m (the maximum range being 0.8 m), 7 groups (63 measurements) have a range of 0.3-0.5 m, and 3 groups (11 measurements) have a range of less than 0.3 m.

Altitudes were also measured along 6 lines of bores approximately at right angles to the main carse shoreline. The ground levels along lines I, II, III, IV, and VI show no general slope away from the back-feature, whereas those along line V do (Figs. 4.3 & 4.4). A line of altitude measurements between borehole BB-7 (line IV) and the main Farg fan, and extending a short distance onto the latter, show that the carse surface rises slightly from 9.6-10.1 m away from the fan to 10.2-10.3 m at its edge. The ground then rises more sharply on the sand and gravel of the fan, to 11.6 m within 50 m of the edge (B.189-213, Appendix I). The morphological break between the main carse and the fan, as determined by a line of levelled heights, thus corresponds exactly with the abrupt change in surface materials noted earlier (sec.II1b), although the carse surface is a little higher than usual within a distance of about 150 m of this break.

d) Altitudinal data : lower postglacial terraces

The height data obtained on the terraces within the Earn trench are summarized in Table 4-4, in which features that slope markedly along their length are differentiated by an asterisk from those that do not. All measurable features were measured south of the Earn, but on the north side, no measurements were obtained west of Bridge of Earn or in the core of the large meander at Wester Rhynd because, in view of shortage of time, difficulties of access, and

TABLE 4-4

POSTGLACIAL TERRACE FRAGMENTS LOWER THAN THE MAIN CARSE LEVEL: THE NEWBURGH - BRIDGE OF EARN AREA

Location	Altitude (m O.D.)		No. of hts.	Dist. m	Reference numbers	
	range	mean				
South of the River Earn (in order E-W):						
d. Ferryfield of Carpow	8.9-9.0	8.9	4	150	B.674-7	
e. Nethy Burn	2.8-3.0	2.9	6	400	B.744-9	
f. Gordon	3.7-3.9	3.8	5	300	B.384-8	
g. Gordon	9.1-9.2	9.2	5	300	B.750-4	
h. Culfargie	3.0-3.2	3.2	4	150	B.762-5	
i. Culfargie	3.9-4.1	4.0	3	150	B.766-8	
j. Culfargie	4.3-4.6	4.4	5	300	B.756-60	
k. Elliothead	3.9-4.0	4.0	4	250	B.352-5	
l. Elliothead	3.0-3.3	3.2	9	700	B.369,370,398-404	
*m. Oudenard	3.4-3.6	-	3	200	B.389-91	
*n. Oudenard	4.0-4.5	-	8	500	B.392,393,769-74	
*o. Bridge of Earn	4.2-4.5	-	3	200	B.230,231,236	
*p. Bridge of Earn	4.0-4.8	-	8	350	B.240-7	
(*p_1 Bridge of Earn	3.4-4.0	-	6	350	B.237-9,248-50	)
*q. Dunbarney	4.5-5.5	-	17	750	B.259-75	
(*q_1 Dunbarney	4.5-4.6	-	2	100	B.276,277	)
North of the River Earn (in order W-E):						
*r. Bridge of Earn	3.7-4.4	-	6	400	B.729-34	
s. Bridge of Earn	4.4-4.7	4.6	6	400	B.735-40	
(t. Wallacetown	5.5-6.2	5.8	5	550	B.445,446,469,473, 474	)
u. Mains of Kinmonth	4.4-4.7	4.6	4	200	B.441-4	
v. Mains of Kinmonth	4.0-4.1	4.0	5	300	B.447-51	
w. Mains of Kinmonth	3.2	3.2	6	400	B.455-60	
x. Easter Rhynd	2.6-3.0	2.8	7	600	B.424,425,427,430-2, 435	
y. Easter Rhynd	3.7-3.8	3.7	3	150	B.426,428,429	
(*z. Easter Rhynd	3.6-4.5	-	5	250	B.436-40	)

* These terrace fragments slope markedly along their length, from west to east.

( ) Brackets explained in text.

duplication of features on both sides of the river, they were not considered vital.

Unlike the main carse the lower postglacial terraces are highly fragmented, and cannot be correlated either by morphology without the aid of altitude measurements or on grounds of composition or stratigraphy (sec.II1e). They are undoubtedly former and present floodplains of the River Earn, produced in a zone of transition between fluvial and estuarine environments. The present upstream limit of tidal influence is at the western end of fragment q, and the point at which the terrace fragments in general change from being virtually horizontal to sloping along their length is represented by fragment m. Fragment z is an apparent anomaly in sloping along its length despite its easterly location, but its back-feature is gradual and only marginally suitable for measurement.

Correlation of these features will be considered later (Chap. 9), but it is apparent from Table 4-4 that non-sloping terraces occur at 5 levels: 2.8-3.2 m (fragments e, h, l, w, & x; 32 measurements), 3.7-4.0 m (f, i, k, v, & y; 20 measurements), 4.4-4.6 m (j, s, & u; 15 measurements), 5.8 m (t; 5 measurements), and 8.9-9.2 m (d & g; 9 measurements). The one representative, t, of the fourth level is doubtful because the measurements were obtained on a flat-topped remnant isolated by dissection, possibly from the main carse, in which case it has no relevance to the lower postglacial terrace sequence. The highest fragments, d and g, are only 0.2 m below the main carse level, and it is possible that the otherwise anomalous main carse heights at Eastfield of Dunbarney (sec.II1c) represent this slightly lower carse level.

Despite their close altitudinal spacing, the lowest 3 levels may be differentiated with confidence, firstly because representatives of all 3 occur one above the other at 2 places, and of the lowest 2 at 2 places, and secondly because most of the features are remarkably flat and have sharp back-features. This morphological clarity is reflected in the great consistency of the measurements, fragment h, for example, having a range of 0.2 m (4 measurements), v one of 0.1 m (5 measurements), and w no range at all (6 measurements).

The sloping, fluvial fragments are also very sharp morphologically, but there is difficulty in deciding whether one or two features are present. Fragments p_1 and q_1, for example, situated along the front of p and q respectively, are very narrow and close to the artificial levée and there must be doubts as to whether they are (i) distinctly lower terraces than p and q, (ii) depressions marking the courses of former river channels dissecting p and q, or (iii) depressions resulting from the excavation of material for constructing the levée.

The origin of the above terraces is discussed later (Chap.9).

e) <u>Stratigraphy</u>

The stratigraphy of the carselands excited interest from an early date, due partly to the abundance of riverbank sections, and partly to the presence of a widespread buried peat layer. Old accounts of the carseland stratigraphy, sometimes detailed and accurate in describing the character of the deposits, include the following: W. Taylor (1792), W. Duncan (1794), J. Robertson (1799), Fleming (1823), Buist (1841), J. Anderson (1845), Cumming (1845), D. Duncan (1845), Jamieson (1865), T. Brown (1870), F. Smith (1874), and J. Geikie (1881a,b,c; 1894). Fleming's description referred to the submerged forest exposed in the intertidal zone between Wormit Bay and Newburgh; Jamieson and Geikie summarized the evidence over the whole Earn-Tay basin.

The best exposures of the peat and the overlying carse deposits at present are in the banks of the Earn at the locations shown in Figure 4.3. The peat in these sections is 0.3-0.9 m thick, occurs near high water mark of ordinary spring tides, and is overlain by 4.6-6.7 m of carse deposits. Peat has also been located beneath the main carse by many bores in the Newburgh-Bridge of Earn carselands, including 2 early bores in Newburgh (Buist, 1841; J. Anderson, 1845), 7 out of 18 modern site investigation bores near Bridge of Earn (Fig.4.3 overlay; Fig.4.5), and 47 of the 58 bores sunk by the writer (Figs.4.3 & 4.4). In several of the bores in which a definite peat bed was not reported, abundant plant remains were found at the base of the carse. The peat layer is thus almost ubiquitous beneath the main carse, but all available evidence suggests its absence beneath deposits younger than the main carse. 14 site investigation bores on the lower postglacial terraces near Bridge of Earn (Fig.4.3 overlay; Fig.4.5), and 2 on reclaimed land near the Earn-Tay confluence (SI/B.8, Fig.4.3) and on Mugdrum Island (Coates, 1897), all penetrating far below Ordnance Datum, failed to record peat. Buist (1841, p.43) in a diagrammatic cross-section, depicted a layer of peat beneath raised beach fragment c (Fig.4.2), although he cited no specific evidence of its presence.

The peat consists of sedges and grasses, with occasional mosses and abundant wood remains. The non-arboreal remains include stems, leaves, roots, and seeds of various marsh and heath plants, including Carex (J. Anderson, 1845), Sarothamnus (D. Duncan, 1845), and Equisetum (F. Smith, 1874). Arboreal remains that have been identified include bark, leaves, fruits, roots, branches, and even trunks, of the following genera: Alnus (alder), Corylus (hazel), Betula (birch), Pinus (pine), Salix (willow) and Quercus (oak), of which the first three are of most common occurrence, and the last has been mentioned by only one observer in this area (W. Duncan, 1794). East of Bridge of Earn, the peat contains much wood and is highly compressed, as shown by its toughness and by the oval cross-sections of flat-lying branches and twigs, and it "readily splits into laminae, on the surface of which many small seeds ... appear, together with occasional wing-cases of beetles" (J. Geikie, 1894 p.292). The transition with the overlying carse is fairly gradual, the top few cm of the peat being silty, and the bottom 30-50 cm of the carse being full of both horizontal black streaks of vegetal material, and plant stems passing vertically upwards from the peat. The base of the peat is more sharply defined, but roots penetrate from it into the sandy materials below.

It is therefore clear that, for the most part, the sub-carse peat represents a former land surface that was gradually inundated by estuarine waters, as recognized by Buist (1841), Jamieson (1865), F. Smith (1874), and J. Geikie (1881a, 1894). West of Bridge of Earn, however, the peat in the riverbank sections and in bores BB-56 and 57 (Figs.4.3 & 4.4, line V) is a wholly drifted deposit, as recognized by T. Brown (1870), being really a peaty silty clay with many flat-lying vegetal remains. The areal extent of this facies is not known, but it is probably limited, because one bore (BB-55, Fig.4.4, line V) located 200 m from the riverbank section passed through compact woody peat like that farther east.

The most widespread material immediately beneath the peat (and beneath the carse where the peat is absent) is a grey or brown micaceous fine sand, silty fine sand, or sandy silt, as revealed by all bores penetrating to the sub-peat material along lines II, III, IV, V, and the line of the M.90 motorway, by 4 bores along line VI, and in the riverbank sections east of Bridge of Earn (Figs.4.4 & 4.5). This material is sometimes structureless, as in the Cordon riverbank section (*1, Fig.4.3), and sometimes cross-bedded, as at Carey west of Carey Stank (*2, Fig.4.3). Jamieson (1865) described the peat as resting on laminated clay east of Cordon, but the writer could find no evidence of this. West of Bridge of Earn, the riverbank sections south of the river reveal laminated clayey silt immediately beneath the peat, whilst the Hilton section north of the river (NO 1212 1954) shows a thin bed of clay resting on gravel. By contrast, a sand and gravel deposit was found directly beneath the peat in bores SI/B.6 and 7 and in

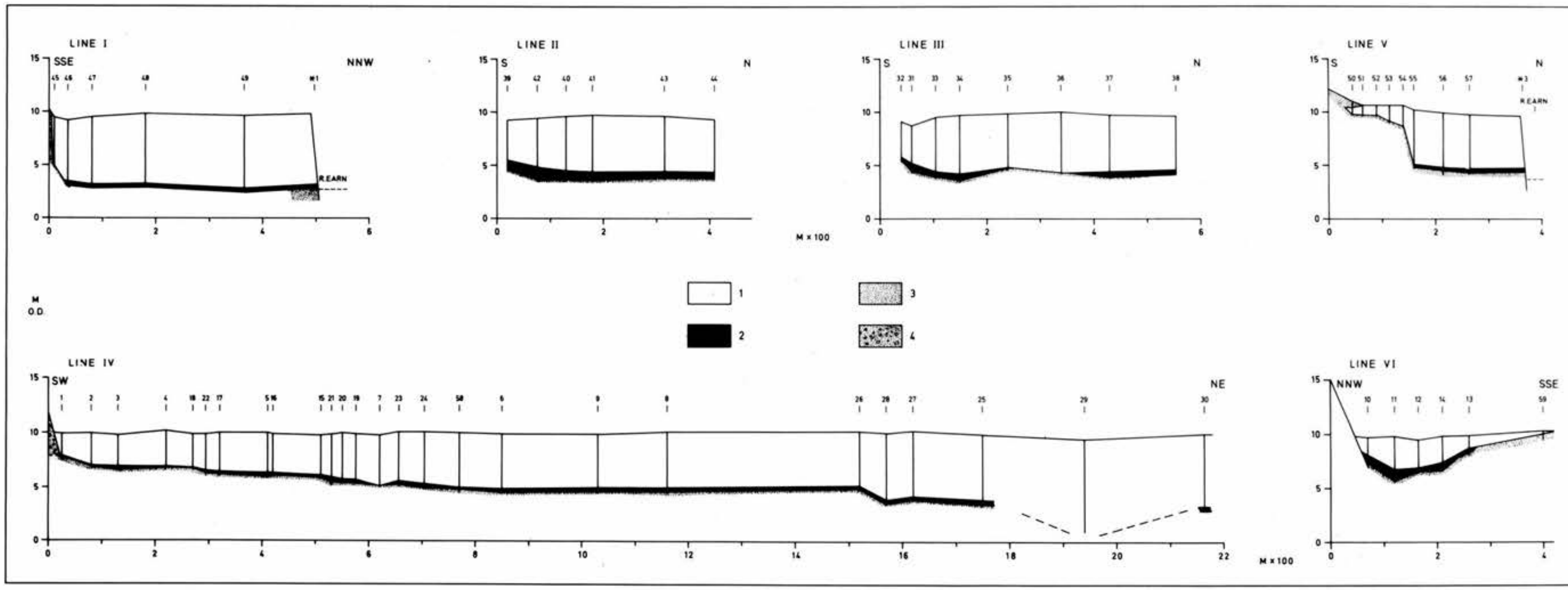


FIGURE 4.4 - Sections through lines of bores in the Newburgh - Bridge of Earn area: lines I to VI. 1, Carse deposits; 2. Peat; 3. Fine sand or silty fine sand; 4. Sand & gravel.

the Carey section east of Carey Stank, and immediately beneath the carse in bores BB-13 and 59 (Fig.4.4, line VI), and SI/B.33 (Fig. 4.5), but these are purely local occurrences. A thin (5-50 mm) iron pan separates the peat from the underlying material at Cordon and Carey.

The origin of the sub-peat material has been ascribed in the literature to both estuarine and fluvial conditions, advocates of the former including J. Robertson (1799) and Jamieson (1865), and of the latter, J. Geikie (1881a,c; 1894). Jamieson cited the laminated clay as evidence of an estuarine origin, whilst Geikie regarded the cross-bedding, occasional gravel, and the apparent downvalley gradient of the peat bed as revealed in riverbank sections, as proof of a fluvial origin. The writer's programme of boring was designed primarily to ascertain the nature and origin of the sub-peat surface, and whilst many more bores will be needed to fully realise this aim, some tentative suggestions may be made.

Lines I to V (Figs.4.3 & 4.4) show the sub-peat surface to be flat over considerable areas. The section through the 5 bores and the riverbank section of line I shows a single flat surface beneath the peat. Although only 1 bore (BB-46) reached the base of the peat, which is extremely tough, the others penetrated well into it, and on the basis of its thickness in the riverbank exposure, in a temporary excavation (NO 1895 1793), and in BB-46, an assumed value of 0.35 m was used for peat thickness in the other bores. The estimated altitude of the sub-peat surface ranges between 2.4 and 3.0 m over a distance of 465 m.

Line II shows an even more regular sub-peat surface the altitude of which, as revealed by 5 of the 6 bores, varies between 3.6 and 3.8 m in a distance of 330 m. The peat is much less tough than that in line I and in the Carey section, 500 m east of line II, where the base of the peat was measured at 3.1 m O.D.

The sub-peat surface along line III is, by contrast, rather irregular, with an altitude variation between 3.6 and 4.7 m in a distance of 500 m, if BB-32, which reached the buried frontal bluff of lateglacial beach fragment E, is excluded. There is a depression in the sub-peat surface beneath the back of the carse, but it is more regular along the outer 215 m of line III, at 3.9-4.3 m, suggesting a buried terrace at about that level.

The 26 bores extending for over 2 km along line IV revealed 4 distinct terraces in the sub-peat surface. The altitude variation of the highest, reached by 4 bores, is between 6.7 and 6.9 m in a distance of 200 m, and of the second between 5.9 and 6.3 m in 215 m (5 bores). Although the altitudinal difference between these features is not great, they are separated by a distinct break where the sub-peat surface drops 0.4 m in a distance of 25 m. The buried surface falls gently and irregularly from the second to the third buried terrace, which is the widest so far revealed, extending for over 800 m along the line of bores at an altitude of 4.5-4.9 m. Its frontal bluff is marked by a drop in the sub-peat surface, from 4.9 to 3.5 m in a distance of 50 m, down to the fourth buried terrace, which is less well defined owing to the wide spacing of the 5 bores, the inner 3 of which (BB-25, 27, & 28) show a sub-peat surface altitude of 3.5-3.9 m over a distance of 180 m. The next bore out (BB-29) penetrated to 0.9 m O.D. without bottoming the carse deposits, and the outermost bore (BB-30), although not encountering true peat, passed through 0.3 m of firm carse clay with many chunks of wood before becoming impenetrable at 3.0 m O.D. It seems likely that these 5 outer bores, spread over a distance of almost 600 m, penetrated to a buried terrace, at 3.5-3.9 m O.D., that is traversed by a valley or channel of unknown depth. This may be a former channel of the Earn.

The 8 bores and riverbank section of line V reveal 2 buried terraces separated by an abrupt fall in the buried surface of 3.9 m in a distance of 20 m. The higher terrace, reached by 3 bores, is only 50 m wide and has an altitude of 9.8 m. The lower terrace, revealed by 3 bores and the riverbank section, shelves towards the Earn, and ranges in altitude between 4.3 and 4.8 m in a distance of over 200 m.

The 6 bores of line VI are the only ones so far sunk by the writer north of the Earn, and the section through the bores confirms the irregular nature of the buried surface in this area mentioned above (sec.II1c), for it shows a depression in the sub-peat surface below the back of the carse, and sandy material almost at the surface at the position of the outermost bore (BB-59). The thinness of the carse about 100-300 m out from the back-feature is well-known by farmers between Hilton and Muirhead, as is its rapid thickening between the buried sandy ridge and the Earn.

The altitude of the base of the peat in the Wester Rhynd river-bank section, although not measured, is similar to that at Cordon.

The site investigation bores through the main carse along the M.90 line (Fig.4.5) also suggest the presence of a buried terrace beneath the peat south of the Earn, at an altitude of 5.0-5.3 m. These bore records are less valuable for the present purpose than the writer's, for the reasons stated earlier (Chap.2), and because several of the bores were sunk using rotary air drill equipment, which gives a generalised and approximate picture of drift stratigraphy as compared with the more accurate shell and auger method. It is therefore possible that other buried terraces occur along this line of bores, which, like line IV, shows a deep channel in the sub-peat surface south of the Earn.

The borehole evidence south of the Earn thus suggests the existence of buried terraces, the greatest number proved in any one staircase being 4 (line IV). The origin and correlation of these features will be considered later (Chap.9) but it may be noted here that the fine-grained and homogeneous nature of the buried terrace materials is more suggestive of an estuarine than of a fluvial origin, and that, since the 9.8 m terrace of line V is so much higher than all the others that it probably has no correlatives in the other lines, the minimum number of buried terraces is 5.

The buried terrace materials along the M.90 line are underlain by an irregular but virtually continuous 1.3 km-wide gravel and coarse sand layer, the top of which varies in altitude between -3.4 and +3.9 m, and the base between -6.6 and +1.4 m (Fig.4.5).

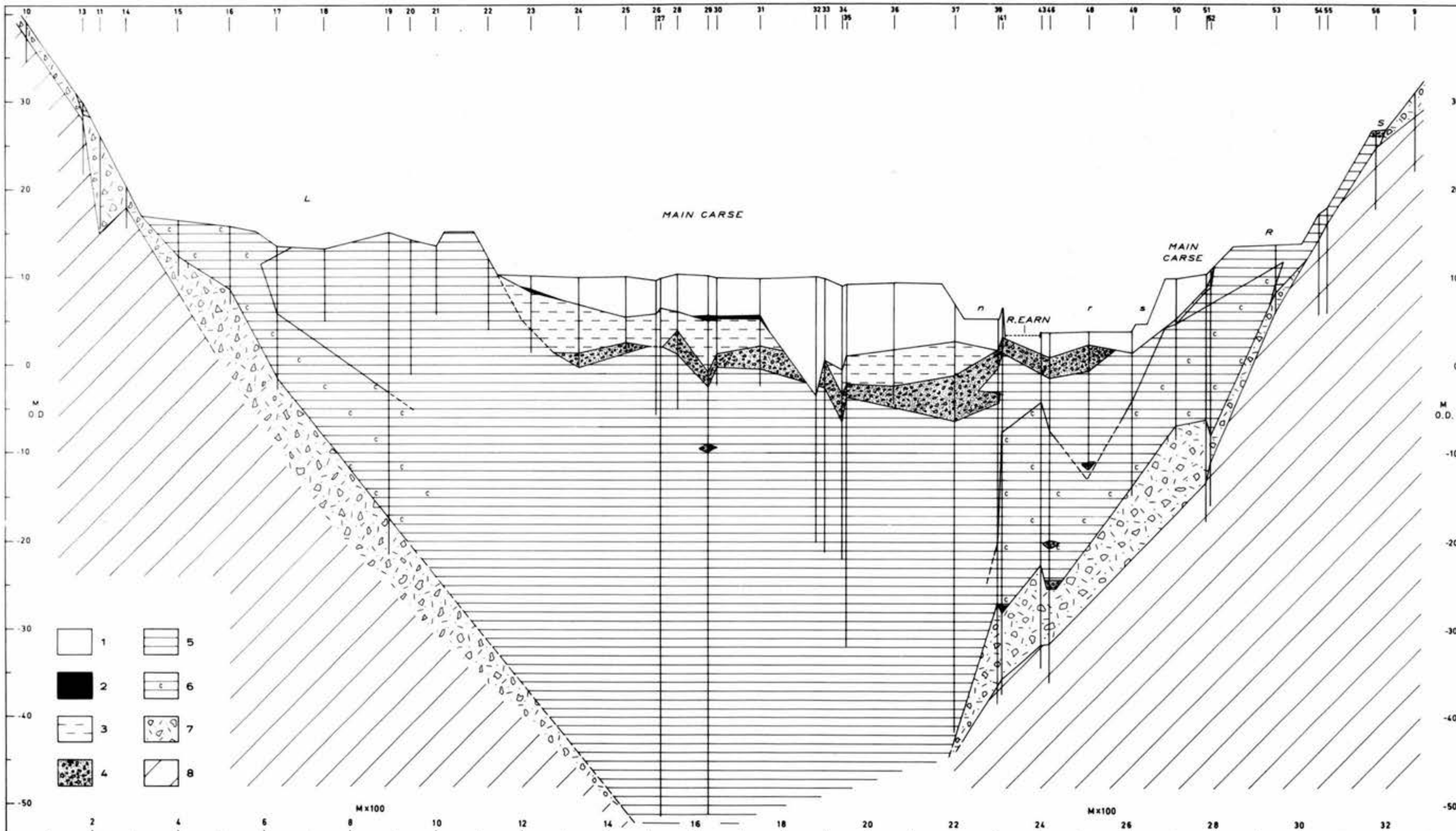


FIGURE 4.5 - Section through the site investigation bores along the line of the M.90 motorway. 1. Carse deposits; 2. Peat; 3. Buried beach deposits; 4. Sand & gravel; 5. Lateglacial estuarine deposits; 6. Same as 5, plastic clay facies; 7. Till; 8. Bedrock.

This layer occurs only beneath the carselands, being entirely absent beneath the visible lateglacial raised beaches, which implies that it postdates the latter. This in turn means that except for the 9.8 m terrace of line V (Chap.8), the buried terraces are not simply a continuation beneath the carse of the sequence of visible lateglacial raised beaches, but represent a distinctly later period of formation. This matter, and the gravel layer, will be discussed more fully later (Chaps.8 & 9). According to both the bore records and the writer's observations, the character of the buried terrace and lateglacial marine deposits is usually very similar, except that scattered stones do not occur in the former but are abundant in the latter, which have been proved down to -51 m O.D. in the centre of the valley. Sometimes, however, the lateglacial marine sediments include a very distinctive laminated, plastic clay, chiefly on the flanks of the valley (Fig.4.5).

f) Age relations

The stratigraphy in the lower Earn carselands may now be summarized thus:

9. Lower postglacial terraces
8. Main carse
7. Sub-carse peat
6. Buried terraces (except the 9.8 m terrace of line V)
5. Gravel and coarse sand layer
4. Lateglacial marine deposits (associated with visible lateglacial raised beaches)
3. Fluvioglacial sand and gravel

2. Till

1. Bedrock

It is assumed that the sand and gravel that occurs immediately above the till in some bores is of fluvioglacial origin. The above stratigraphic relations are illustrated in Figure 4.5.

Pollen analysis and radiocarbon dating of the sub-carse peat have been carried out at 2 sites: Eastfield of Dunbarney and Carey (*3 & *2, Figs.4.3 & 4.4). Peat with wood from the former site, believed to have been collected in 1945 by J.B. Simpson, was dated by radiocarbon assay with the following result (Godwin & Willis, 1961):

Sample Q-421 8,411±157 years B.P.

Pollen analysis suggested formation in zone VIa, which agrees broadly with the radiocarbon age. Unfortunately, there is no evidence concerning the position within the peat bed from which the sample was taken.

At the Carey section, samples of the top and bottom centimetres of peat were obtained by the writer. The sample from the base of the peat was dated by Isotopes Incorporated, with the following result:

Sample I-2796 9,640±140 years B.P.

The sample from the top of the peat was dated by the National Physical Laboratory, the result being as follows (Callow & Hassall, 1970):

Sample NPL-127 7,605±180 years B.P.

These samples were taken from the part of the exposure west of Carey

Stank (Fig.4.3). S.E. Durno took samples for pollen analysis from the peat immediately east of the stank about 250 m from where the writer's samples were obtained, and his results date the base of the peat as middle or late zone IV, which agrees with the radiocarbon date. Insufficient pollen was obtained to date the top of the peat, but analysis of a sample 14 cm down suggests a zone V or early zone VI age (Durno, personal communication). This is consistent with the date for the top of the peat, which indicates a late zone VI age.

A pollen analysis by Simpson (1935) on sub-carse peat collected at Bridge of Earn agreed with an earlier analysis by Erdtman (1928) near Forgandenny (Chap.5), which indicated a boreal age.

The significance of these dates will be discussed later (Chap.9).

2, Lateglacial raised beaches and shorelines

20 lateglacial raised shoreline fragments were measured in the Newburgh-Bridge of Earn area, 12 to the south of the Earn and 8 to the north. Their positions are shown in Figure 4.3, and the altitudinal data summarized in Table 4-5.

a) South of the River Earn

The most extensive lateglacial raised beach fragment, E, is only slightly less flat than the carse, although it is more dissected by valleys and gullies, especially west of the Nethy Burn. It is 5 km long and up to 700 m wide, and has a steep, 12 m-high backslope leading up to fragment F. A section at the upper edge of the

TABLE 4-5

LATEGLACIAL RAISED SHORELINE FRAGMENTS: THE NEWBURGH - BRIDGE OF EARN AREA

Location	Altitude (m O.D.)		No. of hts.	Dist. m	Reference numbers
	range	mean			
South of the River Earn (in order E-W):					
E. Carpow - Abernethy	12.1-13.5	12.8	40	1,950	B.605-10,616-35, 643-56
F. Carpow - Balgonie	25.1-25.9	25.6	17	1,150	B.636-42,660-6, 668-70
G. Broadwell	14.3-14.8	14.6	7	300	B.598-604
H. Ayton	26.7-27.8	27.1	13	550	B.548-60
I. Baiglie	16.0-16.6	16.3	6	550	B.530,531,583,584, 586,587
J. Crossgates	16.3-16.9	16.6	6	200	B.523-8
K. Crossgates	22.2-22.6	22.4	2	50	B.513,515
L. Dron - Summerfield	16.0-17.2	16.7	15	1,350	B.138-42,147-9, 182-8
M. Kilgraston Mains	11.0-11.3	11.2	6	250	B.107-12
(N. Kilgraston Mains	13.7-14.2	14.0	10	600	B.159-68)
(O. Ballendrick	16.5-16.8	16.7	3	150	B.408-10)
P. Freeland	15.8-16.1	16.0	2	50	B.411,412
North of the River Earn (in order from W-E):					
Q. Hilton	11.2-11.6	11.4	3	150	B.357-9
(R. Moncreiffe	16.1-16.8	16.4	4	150	B.724-7)
S. Moncreiffe	28.8-29.6	29.1	7	300	B.503-9
T. Sandyknowes Plantation	13.7-14.1	13.9	5	300	B.475-9
U. Moncreiffe	27.6-29.1	28.4	10	600	B.487-9,492-4, 499-502
*V. Fingask - Balhepburn	11.1-12.2	11.6	19	1,350	B.364-8,372-8;C.338, 339,C.343,344,350-2
*W. Fingask	15.2-16.0	15.6	6	350	B. 361-3;C.340-2
*X. Fingask - Balhepburn	26.6-27.1	26.8	9	550	B.379,380,382,383; C.345-9

* These fragments continue into the Tay valley section of Area C.

( ) Brackets explained in Text.

Nethy Burn valley (NO 1892 1753) showed brown, laminated silty fine sand down to at least 3 m beneath the raised beach surface, the surface composition elsewhere being generally similar, but with occasional small stones. No shoreline measurements were obtained west of Abernethy because the back-feature is obscured by a shallow, dry valley and by the main Farg fan, but 40 heights were measured along almost 2 km of clearly defined shoreline east of Abernethy, ranging between 12.1 and 13.5 m.

Where best developed the flat surface of fragment F attains a width of 250 m, and although it is more dissected by gullies and valleys than E, its clear shoreline was measured at 17 points over a distance of almost 1.2 km, at 25.1-25.9 m. The steep, 5-6 m-high bluff backing the raised beach leads up to the Carpow terrace, of probable fluvioglacial origin (sec.II3). Towards Abernethy, the former shoreline is obscured by a railway embankment, and the terrace has a degraded appearance. The surface composition is sand and rounded gravel with some cobbles. Fragment G is only a metre or so higher than E, from which it is separated by a linear depression, and 7 shoreline measurements ranged from 14.3 to 14.8 m in a distance of 300 m. The surface composition is sand and gravel. Towards Aberargie, the main Farg fan obscures the break between E and G, apparently merging with both. The gradient of the fan edge was shown by 13 measurements (B.532-5, 565-73, Appendix I) along the sharp back-feature that is a morphological continuation of shoreline fragment G, rising from 13.8 to 20.8 m in a distance of 700 m.

Fragment H, almost 1 km long and over 200 m wide, has a surface composition of sand and gravel, and is mostly very flat, although it is broken by two gullies in the east. The very sharp back-feature was shown by 13 measurements over a distance of 550 m to have an altitude of 26.7-27.8 m. The western end of fragment H is intersected by fluvioglacial terrace fragment 4 (sec.II3), which slopes down northeastwards from 28.4 to 24.4 m in 350 m (Table 4-6), suggesting that the formation of beach fragment H was succeeded by dissection and fan deposition related to a lower sea level than that responsible for H.

The apparent merging of the main Farg fan with the lower late-glacial raised beaches also occurs west of the River Farg, where 9 measurements (B.574-82, Appendix I) showed a decline along the western fan edge from 20.6 m in Glen Farg to 16.7 m where the fan appears to merge with beach fragment I, a distance of 750 m. 6 heights along the shoreline of I are consistent at 16.0-16.6 m over a distance of 550 m, although there is a gap of 250 m where the presence of a stream prevented measurement.

Beach fragment J is separated from I by a large gully, and its shoreline altitude, measured at 6 points in 200 m, is similar to that of I, at 16.3-16.9 m. Fragment K is bounded on both sides by gullies, and the measurable shoreline is so short that only 2 heights, of 22.2 and 22.6 m, were obtained.

Fragment L is over 2 km long and up to 800 m wide, and is backed by a clear shoreline and steep backslope. The shoreline altitude was shown by 15 measurements over a distance of almost

1.4 km to range between 16.0 and 17.2 m. The front of the beach is intensively gullied, some gullies reaching back almost to the shoreline. The latter becomes less sharp, and the beach narrows rapidly, towards the west. The beach is crossed near its widest part by the M.90 bores (Fig.4.3 overlay; Fig.4.5), which reveal a composition of laminated clay near the shoreline, changing to fine sand with occasional fine gravel near the front, although the clay is still present at depth.

Fragment M is the lowest lateglacial member of a staircase of 5 steps rising southwestwards from the Earn, the other members being postglacial fragment o and the main carse, and lateglacial fragments N and O. M is a narrow feature of sandy composition, 50 m wide and 300 m long, with an altitude of 11.0-11.3 m (6 measurements in 250 m). Although its shoreline is only 0.5-0.9 m higher than the carse, the two features are clearly distinguished by morphology and composition.

Fragment N, almost 2 km long and 500 m wide, is separated into two parts by the Deich Burn valley. The portion south of the valley is dissected by gullies and is partly obscured by buildings, a railway embankment, and a large sandpit, making measurement impossible. Sections in the sandpit, to a depth of about 3 m, show fine to medium micaceous fine sand with scattered, well rounded, small stones. In some places the sand is remarkably homogeneous, but in others it includes silty masses, and is occasionally cross-bedded, with foresets dipping in opposite directions in successive beds. In its general character, it is similar to the buried terrace materials exposed in the riverbank sections (sec.II1e). The 1 km-long portion of the terrace north of the Deich Burn is backed by a wide, very shallow dry valley, suggesting the possibility of a fluvial origin, but the 10 heights measured along the length of the terrace flat, well away from the depression, do not support this interpretation, for over a distance of 600 m they range between 13.7 and 14.2 m, with no evident overall slope. Since these measurements were taken well away from the back-feature, they are placed in brackets in Table 4-5; on the basis of typical degrees of shelving of raised beaches of similar composition elsewhere in the Earn-Tay area, they are estimated to be no more than about 0.6 m lower than true shoreline altitudes.

Fragment O has a very flat, 1 km-long surface, but no back-feature that is suitable for measurement, because of gullies, valleys, and buildings. 3 height determinations in the centre of the flat range between 16.5 and 16.8 m, and, as in the case of N, are probably up to 0.6 m lower than true shoreline heights.

Fragment P is over 500 m long and 150 m wide, but owing to a gulley and buildings only 2 shoreline measurements were made, at 15.8 and 16.1 m. Exposures of sand were seen at the top edge of the gulley. This fragment extends for about 200 m into Area C, to the west.

A few other lateglacial terrace fragments of probable marine origin south of the Earn were unsuitable for measurement because of back-features that are vague, or obscured by buildings or woods.

b) <u>North of the River Earn</u>

Fragment Q, which was measured at 3 points, at 11.2-11.6 m, is only about a metre higher than the adjacent carse, but like M, it is distinct from the carse in terms of morphology and its sandy composition.

The full extent of fragment R is uncertain because it is partly obscured by woodland, but it is up to 1.2 km long and 250 m wide, with a sandy surface composition. Borehole SI/B.53 (Fig.4.3 overlay; Fig.4.5) passed through over 5 m of sandy clay and clayey fine sand, with a little gravel, before reaching till. Only the western part of the shoreline was suitable for measurement, 4 heights ranging between 16.1 and 16.8 m; even here the back-feature was gradual, so the entry is bracketed in Table 4-5.

Fragment S has a much sharper shoreline feature than R and 7 measurements in a distance of 300 m lay between 28.8 and 29.6 m. The shoreline continues eastwards to fragment U, but there is a distance of about 200 m along which there is no terrace flat. Fragment U, almost 1.2 km long and up to 200 m wide, has a surface composition of sand and fine to medium gravel. The eastern part of the terrace contains a closed depression that might be a kettle, and has a linear depression along the back, but the western part was measured at 10 points in 600 m, showing an altitude of 27.6-29.1 m.

A staircase of 3 lateglacial raised beaches (V, W, X) occurs around the eastern end of Moncreiffe Hill, so that, including the main carse and lower postglacial fragments u, v, and w, there are

7 marine terraces one above the other in the eastern part of Area B north of the Earn. All three lateglacial features have a surface composition of sand and gravel, and all continue into Area C (Fig.5.2). The lowest, V, is also the most extensive, with a maximal width of 250 m and a measured shoreline length of almost 1.4 km. The 19 measured altitudes lie between 11.1 and 12.2 m. The middle feature, W, is shorter and narrower, with a length and maximal width of 450 m and 120 m respectively. Its surface is less regular than that of V, but its shoreline is sharp, at 15.2-16.0 m (6 measurements in 350 m). The highest terraces, X, with a width of only 100 m, lies at 26.6-27.1 m (9 measurements in 550 m).

3. Fluvioglacial features

Fluvioglacial features are not abundant in the Newburgh-Bridge of Earn area, and there are no large-scale and complex assemblages of fluvioglacial landforms to compare with those in parts of Areas A and C. Terraces and other landforms of probable fluvioglacial origin occur sporadically, but lack of evidence precludes much inference concerning their relationship to each other or to the raised shorelines.

For about 1½ km west of Newburgh, the lower slopes of the Ochils, below about 75 m O.D., become gentler and assume a rolling appearance, with a surface composition of sand and gravel. At first, it is not clear whether the undulations are constructional or the result of dissection, but there are some definite dry channels, indicating that meltwater erosion is at least partly responsible. Apart from a large meltwater channel that runs along the slope above raised beach fragment F for 600 m, the channels are mostly 3-5 m deep and 10-15 m wide, and frequently peter out in rather vague depressions. Nevertheless, there is sufficient continuity to recognize an interconnecting channel system comprising elements running along the slope before bending downslope and petering out at about 30 m O.D. These characteristics suggest meltwaters flowing in a submarginal position.

Several of the channels terminate downslope at the edge of a depression, roughly delimited by the 30 m contour (Fig.4.3), and partly occupied by a stream. Unlike an ordinary river valley, it widens towards its head, which is streamless and once contained a lake, the draining of which revealed an accumulation of peat (J. Anderson, 1845). It also has irregular sides, and is probably a dead-ice hollow, which means that the large gravel ridge that bounds it on the north is at least partly of ice-contact origin. The ridge is 250 m wide in places, has a fairly sharp, slightly sinuous crest at about 41 m O.D. (O.S. spot height), and is fringed on the north and west by a narrow terrace that was unsuitable for measurement, but lies a little below the 30 m contour. According to Buist (1841) the gravel of the ridge rests on till, the junction being just below high water mark.

The terrace fringing the ridge apparently continues the Carpow terrace, which occurs above raised beach fragment F, and whose surface, up to 500 m wide, is too irregular for measurement of any consistent feature. It is clear from the erratic wandering of the 30 m contour across the terrace that the flat remnants only just clear this altitude. Surface exposures revealed coarse sand and gravel, including cobbles up to 15 cm in diameter. The closed depressions and former water courses dissecting its surface, together with the coarseness of the deposit and the absence of raised shorelines at this altitude nearby, all suggest a fluvioglacial origin.

The above characteristics of the fluvioglacial landforms between Newburgh and Abernethy suggest that they were formed in association with a wasting ice-mass whose margin was receding downslope and westwards, and there is evidence of two stages in their formation. The first stage is represented by the submarginal meltwater channel system, which was possibly contemporaneous with the gravel ridge and adjacent dead-ice hollow, and associated with an ice margin that lay at or east of Newburgh. The second stage is represented by the Carpow terrace and the terrace fringing the ridge; the combined feature slopes eastwards from just above to just below 30 m O.D., and was associated with an ice margin near or west of Carpow, according to whether the terrace is ice-marginal or proglacial respectively. There is no evidence linking the terrace with raised shorelines, but it seems highly probable that the sea in this locality has never stood higher than just below 30 m since deglaciation.

Evidence of fluvioglacial landforms elsewhere is confined to scattered terrace fragments, only 4 of which were measurable (Table 4-6), and a few meltwater channels. This statement excludes the main Farg fan, discussed above in relation to lateglacial raised

TABLE 4-6

FLUVIOGLACIAL TERRACE FRAGMENTS: THE NEWBURGH - BRIDGE OF EARN AREA

Location	Altitude range (m O.D.)	No.of hts.	Dist. m	Reference numbers
4. Ayton	24.4-28.4	8	350	B.536-43
5. Baiglie	29.3-32.7	7	300	B.516-22
(6. Moncreiffe	35.7-37.5	3	100	B.510-12)
7. Moncreiffe	30.8-32.6	4	150	B.495-8

( ) Brackets explained in text.

shorelines (sec.II2a). Terrace fragment 4, also mentioned above (sec.II2a), can be regarded as a remnant of an upper Farg fan. These features may have been fluvial and/or deltaic features of lateglacial age rather than strictly fluvioglacial features; it is not known whether their water and sediment came from ice-covered or extraglacial areas. On each side of the entrance to Glen Farg is a terrace at well above 30 m, possibly remnants of a higher level fan.

Terrace fragment 5 is an irregular feature of marginal suitability for measurement, sloping down eastwards from about 33 to 30 m in 300 m (7 measurements), and is morphologically continuous with the larger, gullied terrace overlooking the Dron Burn fan. Both features have a surface composition near the back-feature of sand and gravel, but the soil at the front edges and on part of the slopes below is clayey, and the 1:63,360 Soil Survey map (Sheet 48 & 49, 1968) suggests the presence of marine clay. It is not certain whether this clay is a veneer over the front of the terraces, or whether it underlies the gravel and has been exposed by denudation, but the latter is considered more likely, as in an analogous case north of Perth (Chap.5).

Terrace fragment 6 was found by 3 measurements to have a reverse slope of 1.8 m, from 37.5 m at the front to 35.7-35.8 m at the back. Fragment 7 is a small but clear terrace that slopes down eastwards from 32.6 to 30.8 m in 160 m.

The few meltwater channels in the western part of the area include some large features cut partly or wholly in bedrock, and containing underfit streams.

CHAPTER FIVE

AREA C - THE EARN AND TAY VALLEYS

Introduction

Area C extends westwards up the Earn valley from Area B, and northwestwards up the Tay valley from Areas B and D (Fig.1.2). It comprises the 13 km-long tract of Strathearn between National Grid eastings NO 10 and NN 97, and the Tay valley from northing NO 20 and easting NO 18 in the southeast to northing NO 33 in the north, a south-north distance of 13 km.

Although lateglacial and postglacial raised beaches are well represented in the lower reaches of both valleys, fluvioglacial landforms and deposits dominate the scene elsewhere, and there is evidence concerning the relationship between shoreline displacement and a major lateglacial readvance of the ice into the area.

The field evidence is presented for convenience on 3 maps:-

Figure 5.1: The Earn valley from Freeland to Aberuthven

Figure 5.2: The Tay valley from Balhepburn to Perth

Figure 5.3: The Tay valley from Perth to Stanley.

The meandering River Earn flows from west to east along the northern edge of its valley, and the bounding hillslopes on the north rise steeply within a few hundred metres of the present floodplain. South of the river, however, a terraced expanse up to 3 km broad intervenes between the floodplain and the till-clad slopes of the Ochils. East of the Water of May, where the valley narrows somewhat, raised beaches predominate in this terraced tract, but to the west only fluvial and fluvioglacial terraces occur.

In the Tay valley the river, much larger than the Earn, winds its way in a general north-south direction from the confines of a rock-cut gorge east of Stanley to the southern part of Perth, where it bifurcates around Friarton Island and, on rejoining, swings sharply through a right angle to flow east and southeast towards its confluence with the Earn. North of Perth the bounding hillslopes are fairly gentle, and fluvial and fluvioglacial terraces abound on both sides of the river, although no raised beaches occur north of Sherifftown. Fluvioglacial landforms are also abundant in the right-bank tributary valleys of the River Almond, Shochie Burn, and Ordie Burn, although detailed mapping was not carried out in the latter two valleys. In and east of Perth the bounding hillslopes steepen dramatically as the valley breaches the Sidlaw Hills, and the terraces flanking the river are mostly of estuarine origin. The Tay terraces in general were regarded by Maclaren (1843) as of marine, and by Richardson (1884) as of fluvial, origin.

No levelling was carried out west of the Water of May in the Earn valley, or north of Luncarty in the Tay, because it is clear that only fluvioglacial and fluvial terraces occur beyond these limits, and because the resolution of these highly dissected features into a coherent pattern would represent a considerable research project in its own right, involving work extending well

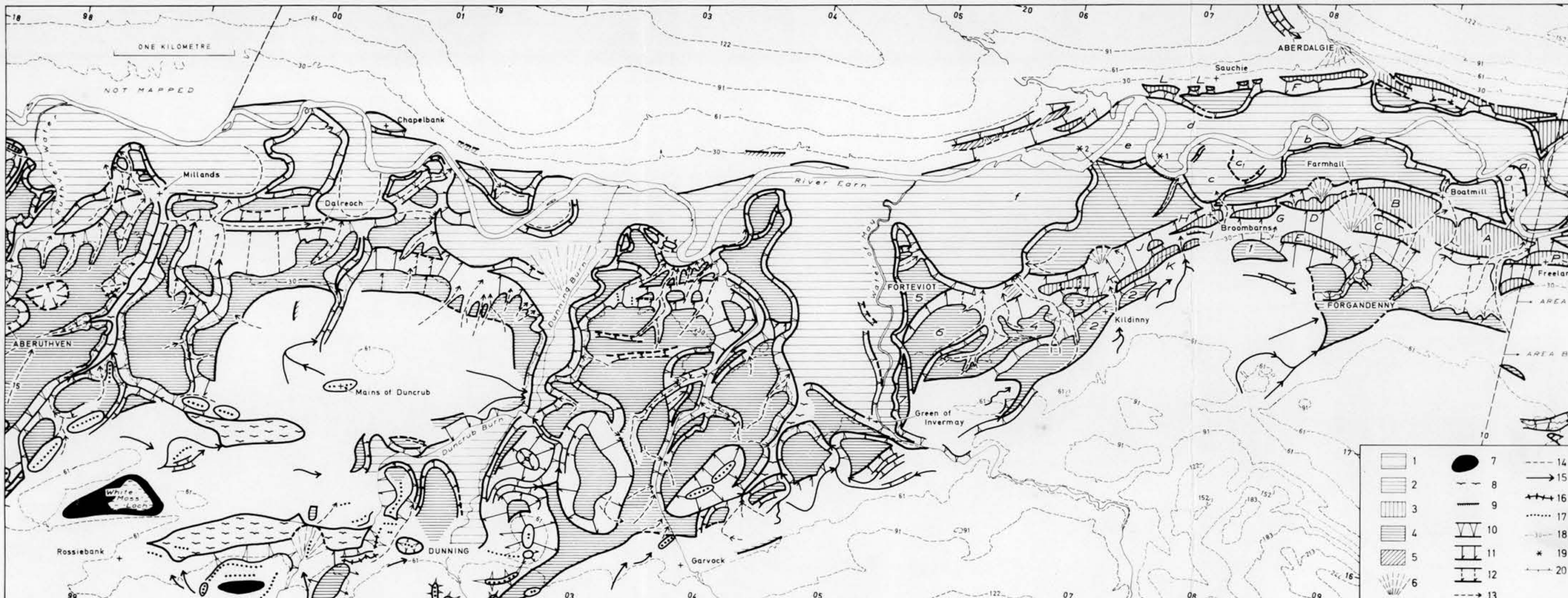


FIGURE 5.1 - The Earn valley from Freeland to Aberuthven. 1. Postglacial alluvial flat; 2. Main carse; 3. Lateglacial raised beach; 4. Fluvioglacial terrace; 5. Step of unknown origin; 6. Alluvial fan; 7. Closed depression; 8. Marshy flat; 9. River cliff; 10-12. Steep, moderate, and gentle slopes; 13. Gully or abandoned river channel; 14. Linear depression; 15. Meltwater channel; 16. Sharp-crested ridge of sand & gravel; 17. Rounded-crested ridge of sand & gravel; 18. Contour (m O.D.); 19. Exposure studied in detail; 20. Line of bores.

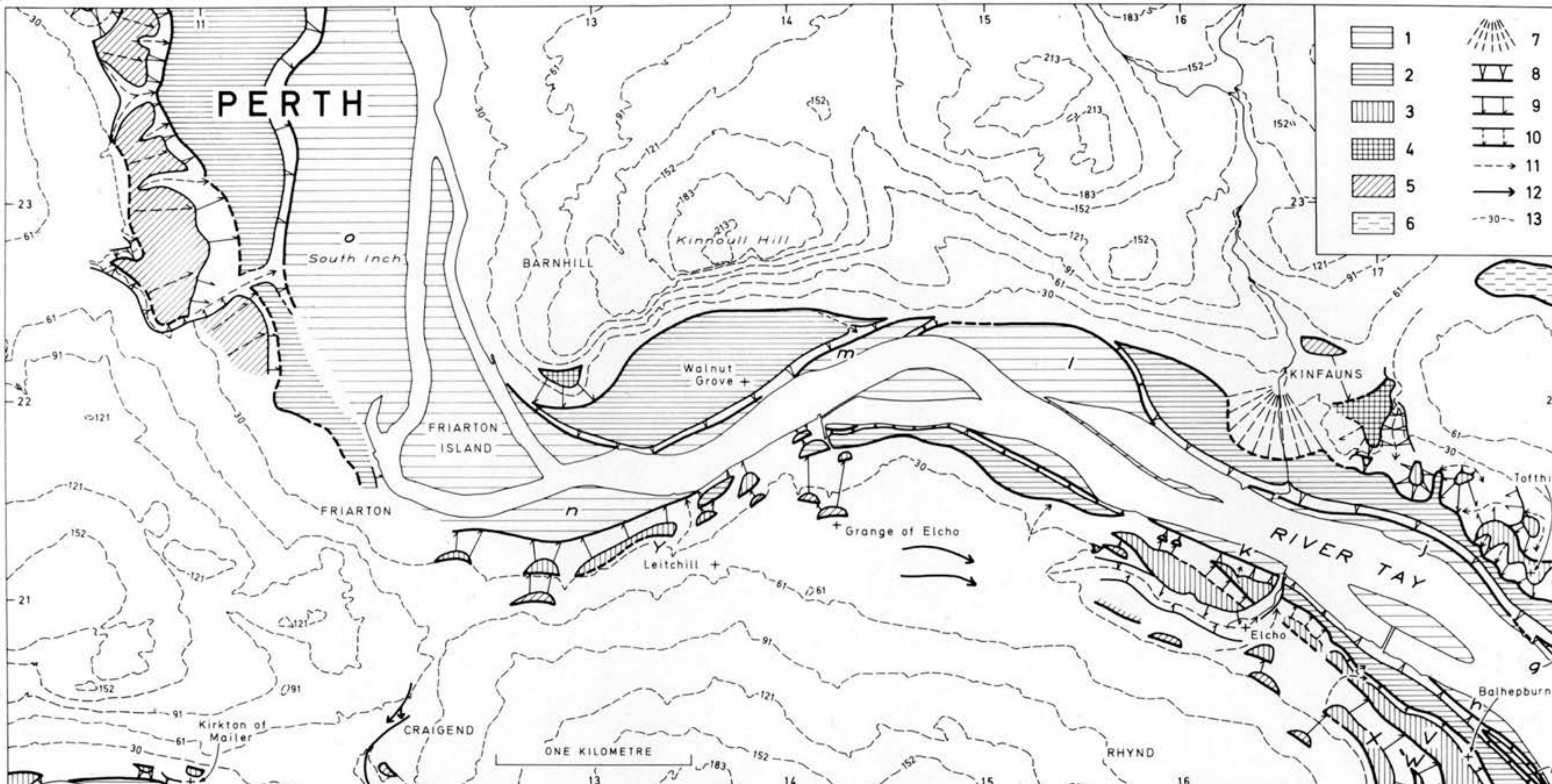
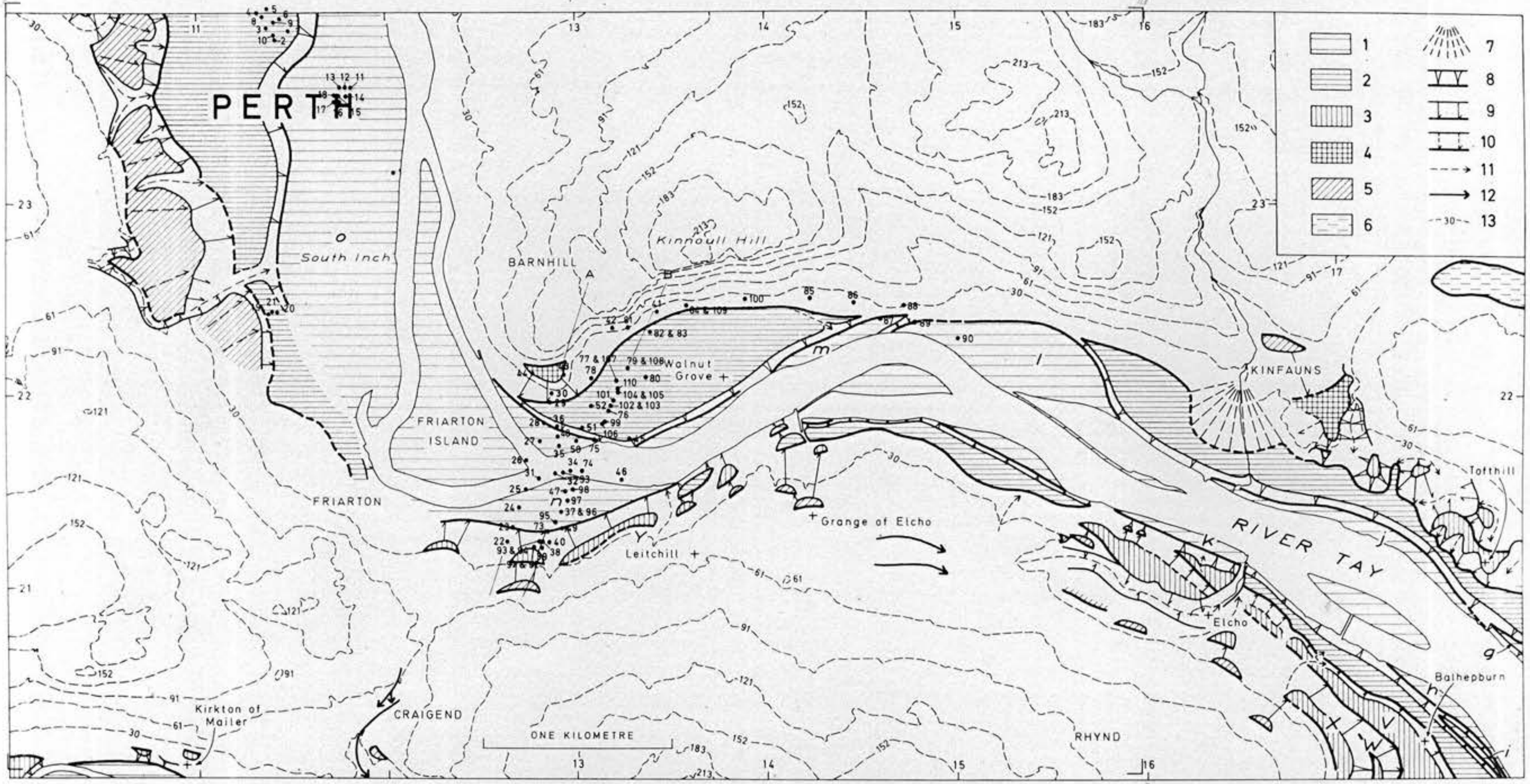


FIGURE 5.2 - The Tay valley from Balhepburn to Perth. 1. Lower postglacial flat; 2. Main carse; 3. Lateglacial raised beach; 4. Fluvioglacial terrace; 5. Step of unknown origin; 6. Lake flat; 7. Alluvial fan; 8-10. Steep, moderate, and gentle slopes; 11. Gully; 12. Meltwater channel; 13. Contour (m O.D.).



POSITIONS OF SITE INVESTIGATION BORES

FIGURE 5.2 - The Tay valley from Balhepburn to Perth. 1. Lower postglacial flat; 2. Main carse; 3. Lateglacial raised beach; 4. Fluvioglacial terrace; 5. Step of unknown origin; 6. Lake flat; 7. Alluvial fan; 8-10. Steep, moderate, and gentle slopes; 11. Gully; 12. Meltwater channel; 13. Contour (m O.D.).

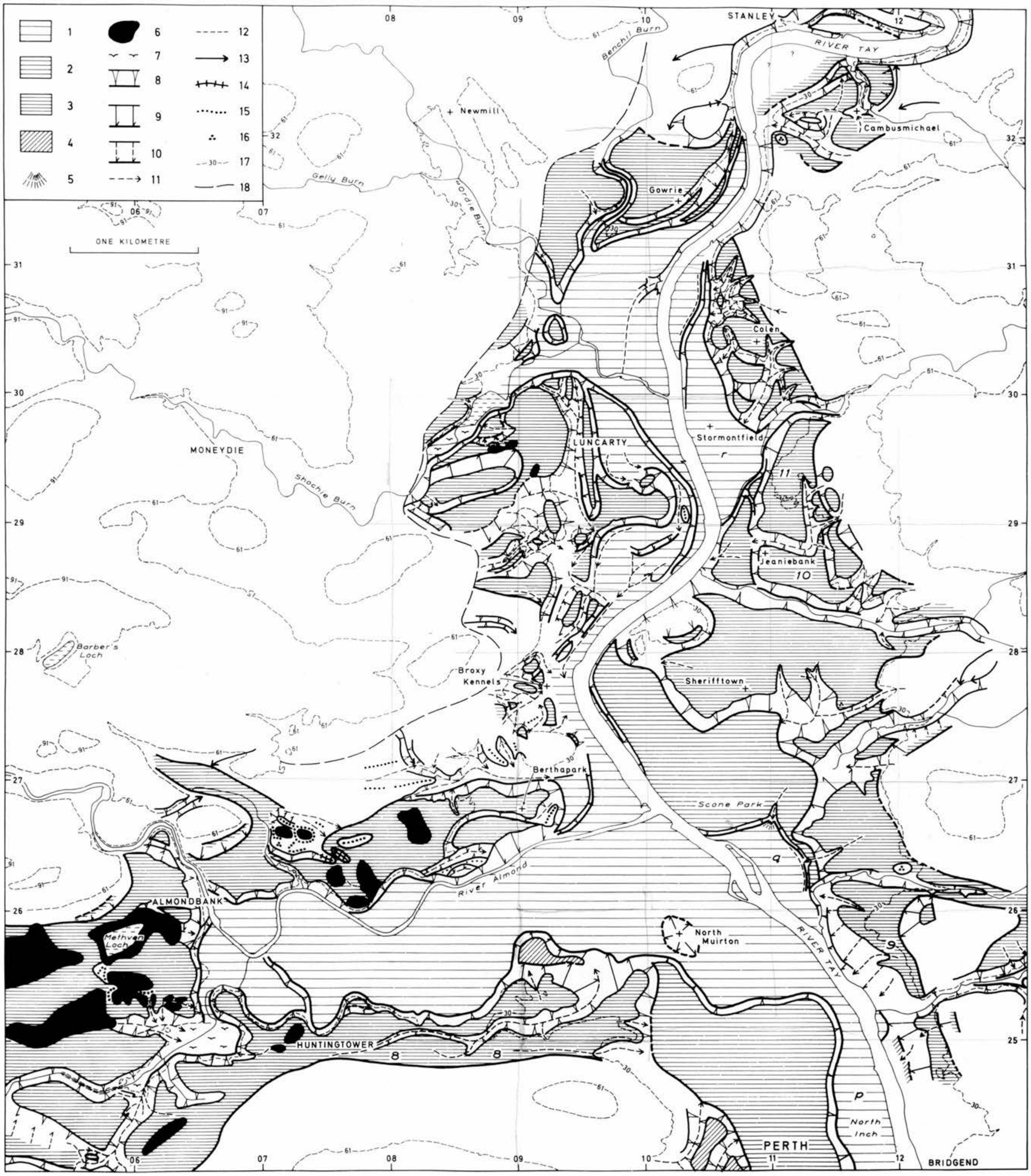


FIGURE 5.3 - The Tay valley from Perth to Stanley. 1. Postglacial river flat; 2. Main carse; 3. Fluvioglacial terrace; 4. Step of unknown origin; 5. Alluvial fan; 6. Kettle; 7. Alluvium; 8-10. Steep, moderate, and gentle slopes; 11. Gully or abandoned river channel; 12. Linear depression; 13. Meltwater channel; 14. Sharp-crested ridge of sand & gravel; 15. Rounded-crested ridge of sand & gravel; 16. Conical mound of sand & gravel; 17. Contour (m O.D.); 18. Limit of detailed mapping (where below 61 m). Overlay in pocket at back.

up both valleys.

1. Lateglacial landforms and deposits

a) Raised shorelines and beaches

12 lateglacial raised shoreline fragments were measured in the Earn valley section of Area C, 2(F & L) being located north of the Earn and the remainder to the south. Their positions are shown in Figure 5.1, and the altitudinal data are summarized in Table 5-1.

The predominantly flat surface of fragment A is 300 m wide and 600 m long, but owing to the presence of gullies and other irregularities the shoreline was measured only over a distance of 100 m, at 14.7-14.9 m (3 measurements). A low bluff separates fragment A from the western part of P (Area B), although gullies partly obscure the relationship between the two features.

Fragment B is morphologically continuous with A, although there is a distance between them of more than 300 m over which gullying has made it difficult to locate the shoreline. The width of B is similar to that of A, and the altitude, measured at 4 points over a distance of 200 m, is 14.6-15.0 m. Above B, and separated from it by a gentle slope, is fragment C, with a maximal width of 150 m and a 250 m length of measured shoreline at 17.9-18.3 m (5 measurements).

Fragments B and C become lost westwards in a large alluvial fan, to the west of which is fragment D, with a rather uneven, narrow, gullied surface that made measurement difficult. Only 2 shoreline measurements were obtained, of 13.0 and 13.2 m respectively. The backslope of D rises fairly steeply to a narrow (100 m-wide) but very distinct terrace, E, the sharp back-feature of which, measured

TABLE 5-1

LATEGLACIAL RAISED SHORELINE FRAGMENTS: EARN AND TAY VALLEYS

Location	Altitude (m O.D.)		No. of hts.	Dist m	Reference numbers
	range	mean			
Earn valley (in order from east to west):					
A. Boatmill	14.7-14.9	14.8	3	100	C.129-31
B. Farmhall	14.6-15.0	14.9	4	200	C.125-8
C. Farmhall	17.9-18.3	18.1	5	250	C.132-6
(D. Farmhall	13.0-13.2	13.1	2	100	C.137,138)
E. Forgandenny	30.9-31.7	31.3	5	350	C.180-4
F. Aberdalgie N	18.4-19.0	18.7	4	150	C.331-4
G. Broombarns	14.5-14.8	14.6	5	200	C.68-72
H. Broombarns	15.5-16.0	15.8	4	200	C.63,64,66,67
(I. Broombarns	17.3-17.6	17.4	2	50	C.61,62)
J. Broombarns	20.9-21.0	21.0	3	100	C.53-5
K. Kildinny	31.6-32.3	31.8	8	650	C.56,57,59,60,173-6
(L. Sauchie N	17.6-18.7	18.2	4	400	C.196,197,204,205)
Tay valley (in order from east to west):					
*V. Fingask - Balhepburn	11.1-12.2	11.6	19	1,350	B.364-8,372-8; C.338,339,C.343, 344,350-2
*W. Fingask	15.2-16.0	15.6	6	350	B.361-3;340-2
*X. Fingask - Balhepburn	26.6-27.1	26.8	9	550	B.379,380,382,383; C.345-9
(Y. Leitchill	28.1-28.2	28.2	2	50	C.321,322)

*These fragments continue into Area B.

N indicates fragments located north of the river; all others are to the south.

( ) Brackets explained in text.

at 5 points in 350 m, lies at 30.9-31.7 m.

Fragment F, north of the Earn, is a narrow but very clear terrace below the alluvial fan at Aberdalgie. Its altitude, as measured at 4 points in 150 m, varies from 18.4 to 19.0 m.

Fragment G has a low frontal bluff overlooking the carse and the western end of fragment D, and a long, fairly steep backslope rising to beach fragment E and fluvioglacial terrace fragment 1. Bedrock crops out in a projection of the backslope behind the overlap of D and G. The surface of the latter is only 100 m or less wide, but it has a very sharp and regular back-feature, as shown by the small altitude range, between 14.5 and 14.8 m, covered by the 5 measurements in a distance of 200 m.

H is the lowest of a staircase of 3 lateglacial raised beaches rising above the carse at Broombarns, the others being I and K. H has a maximal width of 130 m and an altitude of 15.5-16.0 m (4 measurements in 200 m). I is a very narrow shelf perched low on the backslope of H, and 2 measurements, of 17.3 and 17.6 m respectively, were obtained. Although the back-feature of this fragment is locally sharp, its very restricted occurrence makes it necessary to treat the data with reserve. K, by contrast, is a pronounced step which, although never more than 100 m wide, extends unbroken, apart from two small gullies, for a distance of 1 km. It merges westwards into fluvioglacial terrace fragment 3. Its shoreline was sharp enough for measurement over a distance of about 650 m, 8 measurements ranging between 31.6 and 32.3 m.

Fragment J is a small terrace at the base of the steep frontal bluff of K, and overlooking the western end of H. Its altitude, measured at 3 points in 100 m, is 20.9-21.0 m.

L, north of the Earn, is really a group of 3 small fragments separated by gullied embayments. The altitude of 4 measurements in a distance of 400 m ranges between 17.6 and 18.7 m, showing a greater variability than on other fragments in this area. The 2 measurements on the largest fragment (18.5 & 18.7 m) are distinctly higher than those obtained on the smaller fragments (17.6 & 17.8 m), but there is no morphological evidence to suggest the presence of 2 levels, although in view of the gullying it is impossible to be certain of this. This uncertainty makes the data obtained on L of only limited value for purposes of shoreline correlation.

The surface composition of most of the lateglacial raised beach fragments is fine to medium sand containing scattered small stones, as shown by small exposures on fragments A,B, and F. The surface composition of C,E, and K, however, is coarse sand and gravel with stones up to 10 cm in diameter. The coarseness of the material on C and E is probably related to the fact that the backslope is composed of gravel, and K has a similar composition to fluvioglacial terrace 3, with which it merges.

In the Tay valley, the only measurable lateglacial raised shorelines are fragments V,W, and X, which continue into Area B and were described in Chapter 4, and Y, a narrow feature about 500 m long, but with a measurable back-feature only at its eastern end, where 2 measurements 50 m apart gave altitudes of 28.1 and 28.2 m respectively (Fig.5.2, Table 5-1).

b) Fluvioglacial features

Fluvioglacial terraces of great extent dominate the landscape of the Earn valley west of Kildinny, and occur upslope of the raised beaches to the east (Fig.5.1). The easternmost terrace, that on which Forgandenny stands, is an extensive fan that merges at its apex into the floor of a meltwater channel. The material exposed on the surface and in a gravel pit a few metres below the front edge (NO 0872 1868) is coarse gravel, with a wide range of both lithology and degree of rounding. The presence of valleys, gullies, and buildings precluded measurement of the back-feature, but O.S. bench marks indicate a ground level of 43 m near the apex and 41 m near the front. Terrace fragment 1 (Fig.5.1, Table 5-2) is probably contemporaneous with the Forgandenny fan, the distance between them being very small. The back-feature of 1 slopes down eastwards from 41.9 to 40.6 m in a distance of 300 m, equivalent to a gradient of about 4 m/km. The surface composition is similar to that of the fan.

Terrace fragment 2 is the highest of a staircase of 4 fluvioglacial terraces separated from each other by steep bluffs. It is almost 1½ km long and merges at its southwestern end with the flat floor of a large meltwater channel, and its predominantly flat surface, up to 230 m wide, is dissected by several gullies. The 11 altitude measurements, taken well out from the back-feature to avoid a depression, suggest a slope down

TABLE 5-2

FLUVIOGLACIAL TERRACE FRAGMENTS: EARN AND TAY VALLEYS

Location	Altitude (m O.D.) range	No. of hts.	Dist. m	Reference numbers
Earn valley (in order from east to west):				
1. Broombarns	40.6-41.9	5	300	C.186-90
2. Kildinny	42.0-43.3	7	950	C.163-6,177-9
3. Kildinny	33.2-33.6	3	200	C.170-2
4. Kildinny	33.8	2	100	C.167,168
5. Forteviot	22.8-27.6	6	450	C.139-44
6. Forteviot	24.3-34.4	11	700	C.148-58
7. Green of Invermay	31.9-33.8	3	200	C.145-7
Tay valley (in order from south to north):				
8. Huntingtower	36.1-38.0	11	1,450	C.220-5,227-31
(9. Scone	30.8-32.0	6	350	C.307-12)
10. Jeaniebank	28.0-29.6	4	200	C.277-80
11. Jeaniebank	29.9-31.8	8	650	C.269-76

towards the northeast from 43.3 to 42.0-42.2 m in 950 m, equivalent to a gradient of 1.3 m/km.

The other members of the staircase are terrace fragments 3 to 7. Fragments 3 and 4 are really one feature that has been severed by a wide, composite gully. The eastern portion, 3, merges with beach fragment K as noted earlier, the transition from fluvioglacial terrace to raised beach, not discernible by eye, occurring at about 32-33 m. The western portion, 4, is 1.1 km long, but is so severely gullied that its surface could be heighted only at its eastern end, at 33.8 m (2 measurements).

Fragment 6 has a flat, relatively undissected surface up to 330 m wide, and the altitude of its back-feature was shown by 11 measurements to decline regularly northeastwards from 34.4 to 24.3 m in a distance of 700 m, equivalent to a gradient of 14.4 m/km.

The lowest members of the staircase, 5 and 7, are parts of one terrace that has been cut into two by an old meander of the Water of May. The surface is very flat, and the sharp back-feature of the combined terrace slopes down northwards from 33.8 to 22.8 m in a distance of 850 m, equivalent to a gradient of 12.9 m/km.

The alignment of terrace fragments 2 to 7 (Fig.5.1) and the direction in which they slope suggest that the material for their formation came along the southern edge of the Earn valley rather than down the centre, and partly from the Water of

May, and although no levelling was carried out west of the Water of May, it is almost certain that correlatives of terraces 3/4,6, and 5/7 occur in the area between Green of Invermay and Dunning described below.

West of the Water of May the terraces take the form of two great outwash fans or aprons that have been severely dissected by both proglacial meltwater rivers and later gullies. Furthermore, the relatively undissected terrace remnants bear the shallow furrows of former braided channel systems. The complex fan or apron between the Water of May and Dunning Burn is the more dissected of the two, and includes terraces at several different levels, the main level, overlooked by higher terrace remnants, having an altitude of about 38-40 m at its front and over 61 m at its apex, at Dunning (O.S. contour and spot heights), where it is overlooked by several large, steep-sided mounds and ridges of coarse fluvioglacial material. These kames, up to 20 m high, clearly predate the main terrace, although they might be contemporaneous with the highest remnants of the fan complex. Imediately west of Dunning, however, are eskers, kames, kettles, and dead-ice hollows at a considerably lower altitude than that attained by the main terrace, and it therefore seems probable that glacier ice existed here during the deposition of most of the fan complex. Since terraces 3 to 7 may be regarded as a northeastern extension of the fan complex, and terrace 3/4 merges with raised beach fragment K, it follows that the former shoreline of which K is a fragment was formed while ice lay at and west of Dunning, as were terraces 6 and 5/7. The significance of these relationships will be discussed later (Chaps. 8 & 10).

The second outwash fan complex is that around Aberuthven. From an apex up the valley of the Ruthven Water near Auchterarder (off the area of Fig.5.1), it slopes down and widens towards the north and northeast, and comprises an extensive terrace surface that is less intensively dissected than the main Dunning fan, and the remnants of a higher feature. This fan complex probably postdates the Dunning features, for it is difficult to visualize the Aberuthven area being ice-free while ice occupied the area of ice-contact forms between Dunning and the White Moss Loch area, some of which overlook the main Ruthven fan. The latter was probably deposited while the ice margin lay near Auchterarder. Downvalley correlatives of the Ruthven features probably include the fragmented low terraces at the northern fringe of the Dunning complex.

With the exception of terraces at Barnhill and Kinfauns, only fragmentary narrow steps occur above the highest raised shoreline fragments in the Tay valley below Perth (Fig.5.2), and some of these may be structural rather than fluvioglacial. The unmeasurable Barnhill terrace, at about 40 m (Chambers, 1848), has a surface composition of sand and gravel, which was proved to depths of at least 12 and 15 m respectively in two bores located on the frontal bluff (SI/C.43 & 44, Fig.5.2 overlay). The fan-like feature at Kinfauns, at over 30 m, has been largely destroyed by sand and gravel workings.

Extensive fluvioglacial terraces occur north and west of Perth, and possibly in Perth itself, for it is likely that at least parts of the dissected terraced area depicted on the maps as of uncertain origin are fluvioglacial (Figs.5.2 & 5.3). In the eastern part of the Crieff-Methven depression (Fig.1.1), which the River Almond enters at Almondbank, the postglacial flats are flanked on both sides by an extensive spread of fluvioglacial material, the flat surface of which is deeply scored by valleys and gullies, and pitted with several kettles (Fig.5.3). West of Almondbank and Huntingtower the depression is almost completely choked by outwash, and the sharp-lipped kettles reach large dimensions, some being 12-15 m deep and up to 800 m across. Gravel pits in the wall of the largest kettle (NO 0550 2565 & 0530 2550) reveal well sorted, sub- to well rounded, closely packed gravel and cobbles, with false bedding and occasional layers and partings of sand. Contortions, faults, and other collapse structures are evident, produced by the melting-out of the enclosed ice mass.

The back-feature of this outwash spread was measured only between Huntingtower and Perth (terrace 8, Fig.5.3, Table 5-2), where 11 measurements suggest an eastward slope from 38.0 to 36.1 m in 1450 m, equivalent to a gradient of 1.3 m/km. Measurement was not easy because the sharp back-feature is paralleled and encroached upon by a deep channel or gully system.

Outwash terraces occur on both sides of the Tay valley north of Perth (Fig.5.3), sometimes as extensive, little-dissected spreads, as at Sherifftown and Gowrie, and sometimes so greatly dissected that only isolated flat-topped knolls remain. Most terrace fragments are scored to some degree by gullies, but the mounds and knolls around Luncarty and Broxy Kennels have been isolated largely by proglacial meltwater channels, some of which descend to the level of the postglacial flats.

Terrace fragment 9 was measured at 30.8-32.0 m (6 points), with no consistent slope over the measured distance of 350 m. This is probably the combined result of gullying, difficulty in following a consistent back-feature, and the location of the fragment between two valleys that evidently contributed sediment at the time of outwash deposition in the Tay.

Fragments 10 and 11 are really one feature bisected by a large gully. 12 measurements over a distance of 1050 m show a consistent southward slope from 31.8 to 28.0 m, equivalent to a gradient of 3.6 m/km. This is the middle member of a staircase of three outwash terraces, and there are also staircases of three at Colen, Cambusmichael, and Gowrie, and three distinct levels in the mesa-like remnants around Luncarty and Broxy Kennels.

Outwash terraces also extend up the valleys of the Shochie and Ordie Burns, and up the Tay north of Stanley, beyond the area mapped in detail.

c) Stratigraphy and age relations

(i) The stratigraphic sequence

The surface composition of the outwash terraces described above is sand and gravel, often coarse and with subangular to well rounded stones, although the Ruthven fan has a predominantly sandy surface composition with relatively few stones. In both the Earn and Tay valley areas these coarse outwash materials overlie silts and clays, assumed by Simpson (1933) to be of estuarine origin on account of their laminated structure and their similarity and presumed continuity with the fossiliferous marine clays in the Carse of Gowrie (Chap.6). These fine materials beneath gravels are thick and widespread, for in the Earn area, besides the sections recorded by Simpson at Green of Invermay and Templemill, they are exposed in sections at Inverdunning and Millands (Fig.5.1), and in the Tay valley area, they are exposed at the surface at Broxy Kennels, in a section at Berthapark, and were located by site investigation bores near Huntingtower (Fig.5.3) and in the Friarton-Walnut Grove area.

The Green of Invermay section, now overgrown, revealed 3.7 m of distinctly varved silty clay overlain by "morainic deposits" (a term used by Simpson to embrace fluvioglacial as well as glacial deposits), and underlain by till. At Templemill (NN 8743 1900), a riverbank section 10 km upvalley from the western edge of Figure 5.1, the base of the laminated deposit was not seen. In both cases Simpson estimated the top of the estuarine deposit to lie at an altitude of about 27m.

The riverbank section at Inverdunning (NO 0340 1735) is as follows:

Stratified medium sand, occasional fine gravel 2-3 m thick

Stratified coarse sand and fine gravel 0.2-0.3 m thick

Laminated clayey sandy silt (base not seen) 5 m thick

The laminated deposit, which continues below water level, is varved, consisting of alternations of grey micaceous sandy silt and stiff red or grey clay. The thickness of the couplets varies between 3 and 20 mm. The altitude of the top of the silt, although not measured, is definitely below 15 m.

The laminated deposit in the disused Millands clay-pit (NN 9905 1681) consists of repetitions of red sandy silt, yellowish grey silty clay, and brown sand, each triplet being 15-20 cm thick. Only 4 triplets were visible in the overgrown section, and the material overlying the varved deposit was not seen, but the pit occurs in the frontal bluff of an outwash terrace, with a surface composition of sand and gravel and an altitude of about 21 m (O.S. spot height).

In the area around Broxy Kennels (Fig. 5.3) the intense dissection has breached the outwash gravels and incised deeply into the underlying clays, which are extensively exposed at the surface.

The Berthapark section (NO 0839 2625), cliffed by the Almond, is as follows:

Outwash gravels	5 m thick
Varved clay	12 m thick
Till (base not seen)	4 m thick

Noting that the varves vary in thickness between 1.25 and 2.5 cm ($\frac{1}{2}$ & 1 in), and assuming an average thickness of 1.9 cm ($\frac{3}{4}$ in), Simpson estimated the time necessary for the clay to accumulate to be 640 years. He estimated the altitude of the top of the clay to be 27 m.

On the opposite side of the Almond valley from Berthapark, a line of site investigation bores (Fig.5.3 overlay; Fig.5.4) showed a considerable thickness of laminated silts and clays beneath the outwash gravels of terrace 8, the top of the estuarine deposits lying at about 27 m O.D. The latter also continue beneath a gravel layer underlying the postglacial deposits, a relationship that is repeated in the Friarton-Walnut Grove bores (Fig.5.2 overlay; Fig.5.4), which show that both the fine materials and the gravel layer continue beneath the postglacial flats right across the valley. Although of variable thickness, the buried gravel layer has two distinct levels in its surface (section B-B), one beneath the sub-carse peat at about 5 m, and the other beneath the lower postglacial flats at 0-1 m. The age and origin of these buried gravel terraces will be discussed later (Chap.8) in relation to evidence elsewhere; for the present, it will suffice to say that they clearly postdate the lateglacial laminated sediments and predate the sub-carse peat and buried terrace materials (sec.2c).

(ii) The Perth Readvance

From the stratigraphic sequence exposed in the Green of Invermay, Templemill, and Berthapark sections, Simpson drew the important conclusion that two periods of ice advance were separated by a period, estimated to be about 640 years long,

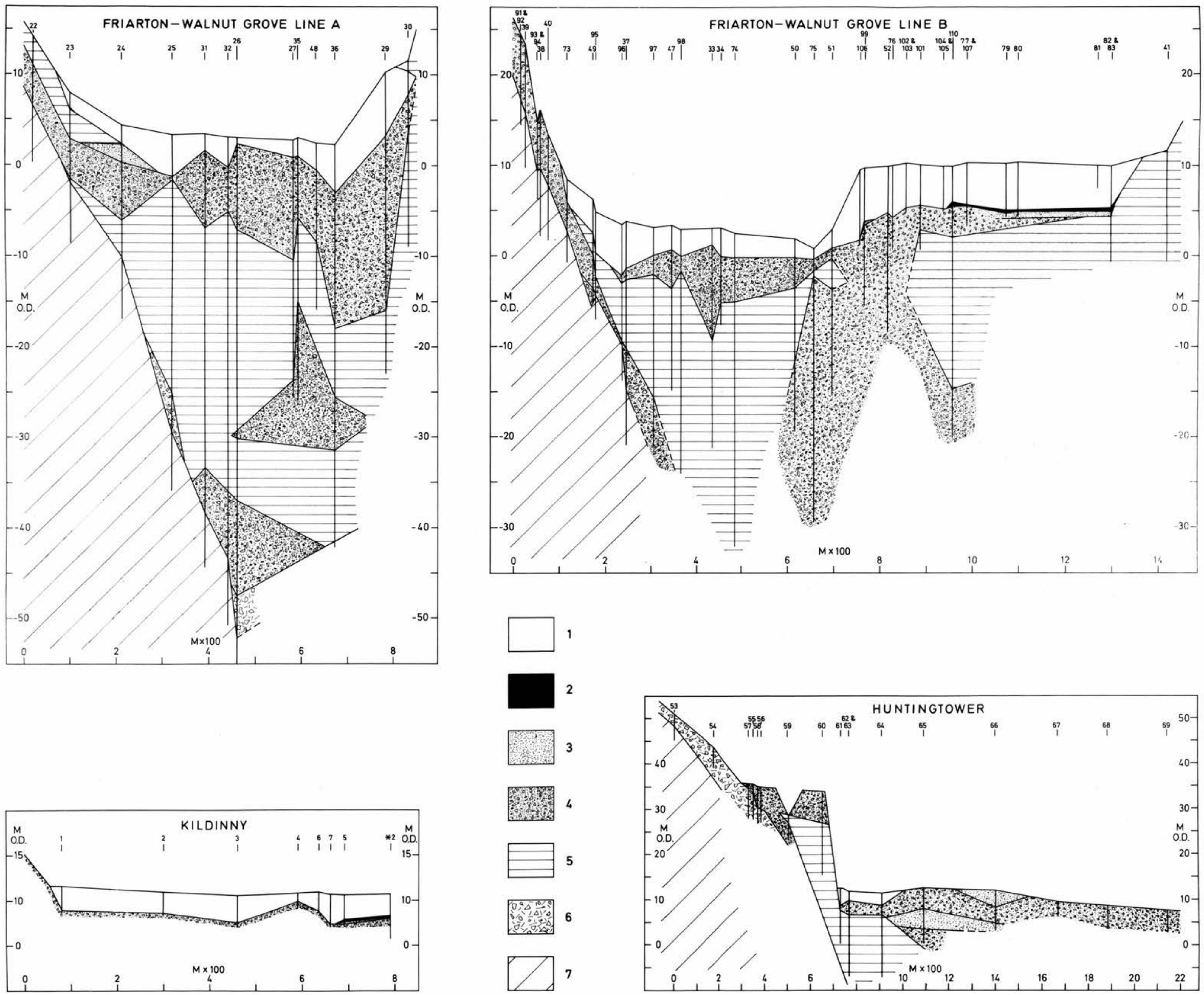


FIGURE 5.4 - Sections through the Friarton-Walnut Grove, Huntingtower, and Kildinny lines of bores. 1. Carse and other postglacial estuarine deposits; 2. Peat; 3. Fine or medium sand; 4. Sand & gravel; 5. Lateglacial estuarine deposits (mostly laminated clays, silts, and sands); 6. Till; 7. Bedrock.

during which estuarine conditions prevailed in the Earn valley as far west as Crieff, and up the Tay and Almond valleys as far as Broxy Kennels and near Almondbank respectively. He termed the later ice advance, responsible for the outwash gravels, the Perth Readvance, the reality and importance of which have more recently been demonstrated over a wider area by Sissons (1963b, 1964a, 1967a).

Although not attempting to define the readvance limits precisely, Simpson clearly stated (1933, p.635) that the ice advanced down the Earn valley into the Firth of Tay, and along the Crieff-Methven depression into the Tay valley, "coming to a halt just north of New Scone." As pointed out by Sissons (1963b), these limits lie too far east, primarily as a result of Simpson's failure to distinguish between proglacial and ice-contact fluvioglacial features; he included outwash formations and ice-contact features such as kames under the term "moraine", and regarded the proglacial meltwater channels that trench the outwash plains and underlying clays as "overflow" or ice-marginal channels.

The limits in the Earn-Tay area suggested by Sissons are supported by the writer's evidence (Fig.5.5). Sissons stated that the limit in the Earn valley is clearly defined on the bounding hillslopes by the upper limit of meltwater channels, and that a line joining this evidence on either side of the valley passes east of the kettle occupied by White Moss Loch (Fig.5.1). The probable limit is at Dunning (sec.2b). The confinement of ice-

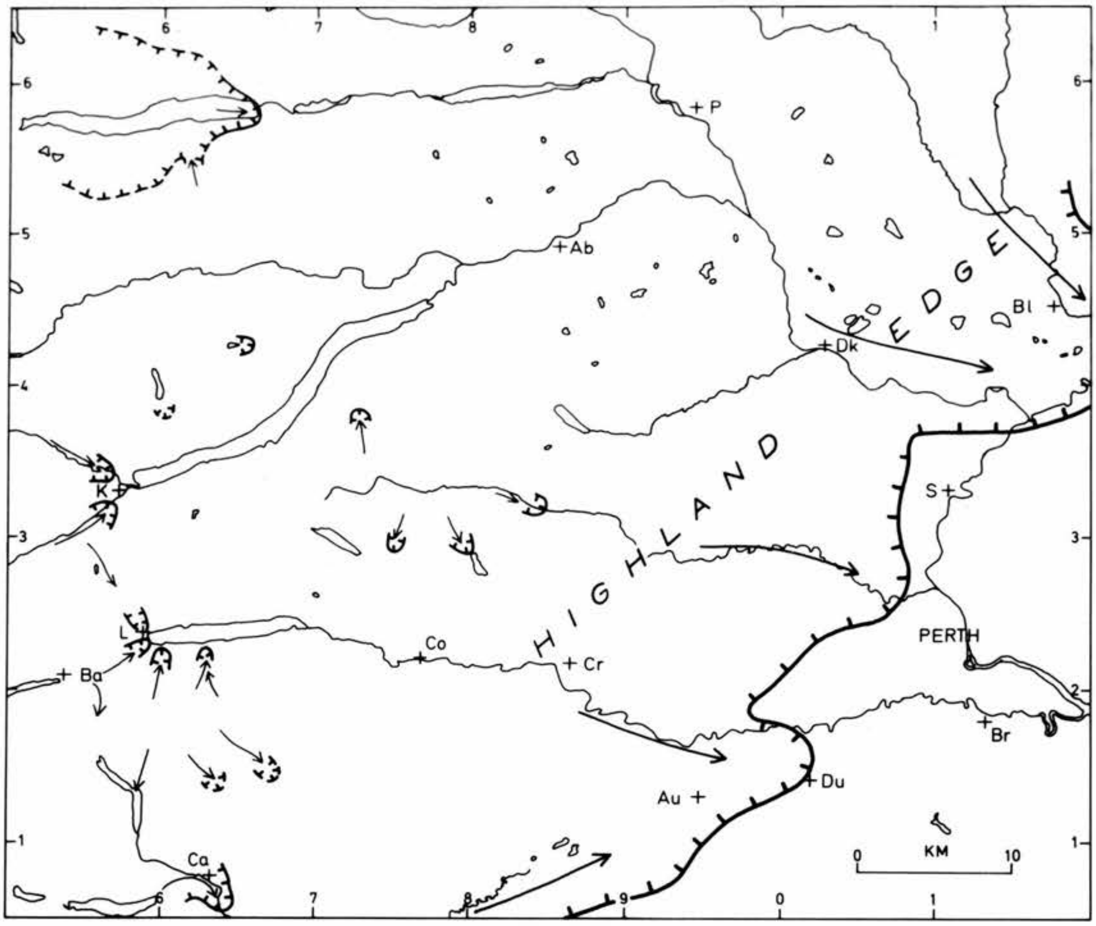


FIGURE 5.5 - Limits of the Perth and Zone III readvances in the Earn - Tay area. The Perth limit (thicker line) is slightly modified after Sissons (1963b); the Zone III limit (thinner lines) is after K.S.R. Thompson (personal communication). Arrows show the directions of former ice movement. Ab. Aberfeldy; Au. Auchterarder; Ba. Balquhidder; Bl. Blairgowrie; Br. Bridge of Earn; Ca. Callander; Co. Comrie; Cr. Crieff; Dk. Dunkeld; Du. Dunning; K. Killin; L. Lochearnhead; P. Pitlochry; S. Stanley.

contact forms to the southern edge of the Earn valley is partly the result of great volumes of meltwater flowing down Strathearn at later stages in the dissipation of Perth Readvance ice, as testified by the abundance of outwash material in the Ruthven fan and its downvalley correlatives, and in still later outwash terraces farther west.

In the Almond valley, the readvance limit is vividly marked by the large kettles pitting the outwash near Almondbank (Fig.5.3); a small area of sharp kame and kettle topography overlooking the main outwash level northeast of Almondbank probably also belongs to the readvance maximum. The kettles have a sharp downvalley limit, and imply that at its maximum the ice extended a short distance from the Highland edge at Almondbank, to within a few hundred metres of the Berthapark section. The kettles near the latter have depths about equal to the thickness of outwash gravel overlying the laminated clay, suggesting that the readvance maximum followed hard upon the cessation of clay deposition, or that the ice advanced into the sea as postulated by Simpson.

The ice probably failed to reach the Tay valley itself between Perth and Stanley, but the intensity of proglacial meltwater dissection and the presence of 3 small kettles near Luncarty suggest that the ice lay near; the kettles were probably produced by the melting of small ice masses rafted into the accumulating outwash sediment. The readvance limit is well marked in the Ordie valley, in which, although detailed mapping was not completed, sufficient was done to show that dissected terraces continue upvalley, the last mesa-like remnants occurring just north of Newmill (Fig.5.3), beyond which kames, eskers, and dead-ice hollows occupy the valley floor. According to Sissons (1963b, pp.160-1), "This southern limit of ice-contact forms can be traced intermittently over the higher ground east of Bankfoot and then continuously on the lower ground towards the Tay, crossing this river south of its confluence with the Isla" (Fig.5.5).

The first attempt to date the Perth Readvance was by G. De Geer (1935), who measured the thickness variations of 59 varves predating the outwash in the Green of Invermay section, and correlated them with his Swedish time-scale. He concluded that they represent the years 13,121-13,063 B.P., a date that, in view of the disrepute into which long-distance varve correlations have understandably fallen, is in remarkably close agreement with the probable date of culmination of the Perth Readvance as deduced from radiocarbon dating, which is about 13,500-13,000 B.P. (Sissons, 1967b; Chap.1).

The relationship of the Perth Readvance to shoreline displacement will be considered later (Chap.8).

2. Postglacial terraces and deposits

a) The main carse

The main carse extends up the Earn valley, continuously to the south of the river and intermittently to the north, as far as Kildinny (Fig.5.1), and intermittently up both sides of the Tay to

Sherifftown (Figs.5.2 & 5.3), the discontinuity in both cases being the result of fluvial erosion. In both valleys the carse fragments have conspicuously flat surfaces furrowed only by a few minor gullies, and steep backslopes and frontal bluffs, and they are much more extensive than the lateglacial raised beaches, reaching maximal widths of 750 m in the Earn valley and 1100 m in the Tay. Nevertheless, they are narrow compared with the large expanses in Areas B and D.

The altitudinal data obtained on the Main Postglacial Raised Shoreline are summarized in Table 5-3. Although some stretches could not be measured, the principal ones being southeast of Aberdalgie (Fig.5.1; poor back-feature), Tofthill - Kinfauns (Fig.5.2; obscured by road and fan), and Perth (Figs.5.2 & 5.3; built-up area), sufficient evidence was obtained from 106 measurements to show a steady gentle rise in shoreline altitude up each valley, as shown by successive fragment means, in order upvalley, as follows: 10.5 m, 10.7 m, 11.2 m, 11.0 m in the Earn valley; 9.8 m, 9.8 m, 10.0 m, 10.1 m, 10.8 m, 11.1 m in the Tay. The total distance covered by the measurements is 3.5 km from east to west in the Earn valley, and about 11 km from southeast to northwest in the Tay.

b) Other postglacial terraces

Within the trench cut through the main carse by the Earn and Tay are younger postglacial terraces. In the Earn valley these are fluvial, for they bear the marks of former meanders, are composed of sandy alluvium, and slope markedly along their length.

TABLE 5-3

THE MAIN POSTGLACIAL RAISED SHORELINE: EARN AND TAY VALLEYS

Location	Altitude (m O.D.) range	Altitude (m O.D.) mean	No. of hts.	Dist. m	Reference numbers
Earn valley (in order from east to west):					
Boatmill	10.2-10.7	10.5	4	150	C.1-4
Farmhall - Broombarns	10.4-11.0	10.7	13	1,000	C.33-45
Sauchie N	10.9-11.6	11.2	6	400	C.198-203
Broombarns - Kildinny	10.8-11.3	11.0	11	1,100	C.48-52,117-22
Tay valley (in order from south east to north west):					
*Glencarse - Tofthill N	9.5-10.1	9.8	12	1,100	C.22;D.386-8,391-4, 398-401
Balhepburn	9.6-10.0	9.8	11	800	C.335-7,353-60
Elcho - Grange of Elcho	9.8-10.3	10.0	12	1,350	C.195,206-8,212-9
Walnut Grove - Barnhill N	9.9-10.4	10.1	14	1,500	C.370-9,382-5
Scone Park N	10.6-11.1	10.8	9	1,000	C.249-57
Sherifftown N	10.9-11.2	11.1	14	1,100	C.232-44,247

*This fragment continues into Area D.

N indicates fragments located north or northeast of the river; all others are to the south or southwest.

In the Tay valley both estuarine and fluvial terraces occur, the change in environment of deposition occurring between fragments m and n (Fig.5.2). The present river is tidal to the northern part of Perth. The altitudinal data are summarized in Table 5-4, in which fragments that exhibit a marked downvalley slope are indicated by a special symbol.

In the Earn valley (Fig.5.1), 2 levels occur in the measured terraces, the present floodplain being represented by fragments a_1 and c_1, fractionally lower than a and c respectively, and separated from them by a clear bluff. In the case of the other fragments there is no clear morphological distinction between terrace and floodplain. The height data show that the lowest terrace of the Earn rises from 5.7 m at Boatmill (fragment a) to 10.2 m at Forteviot (fragment f), in an east-west distance of almost 5 km, equivalent to a gradient of about 0.9 m/km. West of the Water of May, where no levelling was undertaken, the distinction between postglacial and lateglacial terraces is sometimes arbitrary, and in a few cases the wrong symbol may have been applied on the map (Fig.5.1).

The estuarine terraces in the Tay valley (fragments g to m, Fig.5.2, Table 5-4) are similar in form and composition to those east of Bridge of Earn in Area B (Chap.4). The question of correlation is dealt with later (Chap.9), but it may be noted here that 3 distinct levels are represented: 2.7 m (fragment h; 4 measurements), 4.1 -4.6 m (fragments i, j, k, & l; 23 measurements), and 6.4 m (fragments g & m; 15 measurements). Two of the three

TABLE 5-4

OTHER POSTGLACIAL TERRACE FRAGMENTS: EARN AND TAY VALLEYS

Location		Altitude (m O.D.) range	mean	No. of hts.	Dist. m	Reference numbers
Earn valley (in order from east to west):						
"a. Boatmill		5.7-6.0	-	5	200	C.7-11
"a$_1$ Boatmill		5.4-5.5	-	3	200	C.5,6,191
"b. Farmhall		5.6-6.2	-	7	300	C.23-9
"c. Broombarns		6.0-7.3	-	11	750	C.73-80,86-8
"c$_1$ Broombarns		5.9-6.6	-	5	250	C.81-5
"d. Sauchie	N	6.5-7.0	-	8	650	C.323-30
"e. Kildinny		7.1-7.6	-	6	300	C.89-94
"f. Kildinny - Forteviot		7.4-10.2	-	20	1,550	C.95-109,112-6
Tay valley (in order from south east to north west):						
*g. Inchyra	N	6.2-6.6	6.4	13	1,100	C.386,387;D.719-23, 736-41
h. Balhepburn		2.5-2.9	2.7	4	250	C.361-4
i. Balhepburn		4.0-4.2	4.1	5	200	C.365-9
j. Tofthill	N	4.4-4.8	4.6	7	500	C.388-94
k. Elcho		4.3-4.4	4.3	3	200	C.192-4
l. Kinfauns	N	4.2-4.3	4.2	8	550	C.14-21
m. Walnut Grove	N	6.3-6.4	6.4	2	50	C.12,13
"n. Leitchill - Friarton		3.1-4.1	-	8	550	C.313-20
"o. South Inch		4.0-4.6	-	6	500	C.300,301,303-6
"p. North Inch		5.3-5.8	-	10	650	C.286-95
"q. Scone Park	N	6.5-7.5	-	10	850	C.259-68
("r. Stormont-field	N	14.2-16.0	-	4	200	C.281-4)

* This fragment continues into Area D.

" These fragments slope markedly along their length.

N denotes fragments located north or northeast of the river; all others are to the south or southwest.

( ) Brackets explained in text.

levels occur one above the other at three places, and all three occur on either side of the Tay at Balhepburn and Tofthill.

The fluvial fragments, n,o,p, & q (Figs. 5.2 & 5.3, Table 5-4), are really parts of one feature, the continuity of which is broken by a short gap at Friarton and by the river north of Perth, and which is almost certainly the floodplain of the Tay. Its altitude increases upvalley from 3.1 m (fragment n) to 7.5 m (fragment q) in a distance of 5 km, equivalent to a gradient of about 0.9 m/km. Former river channels furrow the surface of fragments o,p, and q, and n has a more uneven surface than the estuarine fragments farther east. Fragment p is of bedded sand, silt and gravel, at least to a depth of 3.7 m (Coates,1900).

Fragment r lies upvalley from the carselands, and is higher than the floodplain, from which it is separated by a low but steep bluff (Fig.5.3). The 4 heights, obtained at the southern end, decrease downvalley from 16.0 to 14.2 m in 200 m, but this gradient may be exaggerated by the proximity of a tributary valley. It is possible that r correlates with the main carse, which lies at 11.1 m more than 1 km farther south; the sharp contrast of its ungullied surface with the intensely gullied fluvioglacial fragments at a higher level support the suggestion that r is of postglacial age.

c) Stratigraphy and age relations

The carseland stratigraphy of Area C, like that of Area B, has long been of interest, and previous writers on the subject include T. Brown (1870), F. Smith (1874), Samuelsson (1910), and Erdtman (1928) in the Earn valley; and Thomson (1845), J. Geikie (1879, 1881d), and Coates (1912) in the Tay.

In the Earn valley, the carseland stratigraphy was examined by the writer in 6 sections, 5 in the south bank of the Earn, and the other in a deep ditch. Their locations are as follows: Boatmill (NO 0983 1916), Farmhall 'A' (NO 0837 1950), Farmhall 'B' (NO 0789 1932), Farmhall 'C' (ditch; NO 0793 1911), Broombarns (*1, Fig.5.1), and Kildinny (*2, Fig.5.1). All show 2.3 to 3.0 m-thick carse deposits similar to those lower down Strathearn (Chap.4), overlying woody peat varying in thickness between 18 and 30 cm, except at Boatmill, where the sub-carse peat is locally absent. The altitude of the base of the peat was measured at Broombarns and Kildinny as 7.0 and 8.2 m respectively.

The peat at Farmhall 'A' is wholly drifted, consisting of dark grey silty clay containing abundant wood and other plant remains; elsewhere, both the in situ and drifted facies of the peat occur. In an unspecified exposure of the latter "near Forgandenny", Samuelsson (1910) found large oak stools, oak cupules, hazel nuts, and *Carex* fruits, and reported that a microscopic analysis showed *Betula* (birch) pollen, fern spores, and diatoms of the genera *Epithemia*, *Gomphonema*, and *Pinnularia*. A later pollen analysis of peat from a different exposure, probably that at Broombarns, indicated a boreal age (Erdtman, 1928), and a sample of *Quercus* (oak) wood from peat shown by pollen analysis to be of zone VIa or VIb age, from the Broombarns section, was dated by radiocarbon assay as follows (Godwin & Willis, 1961):

Sample Q-422   8,344 ± 143 years B.P.

Unfortunately, it is not known from which part of the peat the sample was taken.

The immediate sub-peat material, apart from a 1 cm-thick iron pan in places, is somewhat variable in these sections, being gravel at Boatmill and Farmhall 'B', pink clay or silt in Farmhall 'A' and Kildinny, and silty fine sand at Farmhall 'C' and Broombarns. Laminated silty fine sand/sandy silt occurs beneath the gravel at Boatmill, and is also the material revealed by an adjacent exposure at the front of lateglacial raised beach fragment A, extending from the beach surface down to water level. The immediate sub-carse material encountered by 6 of the 7 bores at Kildinny (Figs.5.1 & 5.4) is sand and gravel, the peat being absent; the other bore, CB-5, showed micaceous silt and silty fine sand containing fine gravel, beneath sub-carse peat. The buried surface revealed by these bores and the Kildinny and Broombarns riverbank sections is irregular, with an altitude variation between 7.4 and 7.9 m.

In the Tay valley, only one carseland section, in the banks of the Tay at Scone Park (NO 1050 2658), was seen by the writer. It showed about 2 m of carse overlying a layer of tree trunks and branches, and other plant remains, resting on dark grey micaceous silt of unknown thickness. Observations by previous workers describe the carse deposits as being similar to those of lower Strathearn (Chap.4), generally containing many plant remains, but no macroscopic estuarine faunal remains, although there has been one report of oyster shells in the carse in Perth (J. Geikie, 1881d). The sub-carse peat has been described by Thomson (1845), J. Geikie (1879), and Coates (1912), as consisting largely of tree trunks and branches, and large pieces of timber were also reported by the last two authors at the base of the carse, resting on the peat. Geikie's find was a dug-out canoe found at Friarton (NO 1176 2192), and Coates reported a beam of timber at Barnhill that bore signs of having been wrought by man.

In Perth, 9 site investigation bores were sunk near the front of the main carse (SI/C.2-10, Fig.5.2), and although 2 bores failed to bottom the carse deposits, the remainder showed 5.6 to 9.8 m- thickness of carse, overlying silty fine sand in turn resting on gravel in 5 bores, and resting directly on the gravel in the other 2. The top of the gravel varies in altitude between -5.2 and +4.1 m, and the base between -9.6 and +2.2 m. Beneath the gravel were recorded silt and silty fine sand down to at least -20.7 m O.D. A carseland bore in Perth reported by McManus (1966) showed the same sequence, the fine lateglacial sediments resting at about -45 m O.D. on till, which was not bottomed at -55 m. Three other carseland bores in Perth (SI/C.19-21) failed to bottom the carse deposits, the lowest altitude at which they were proved being about 1.5 m.

Another group of 8 bores sunk in Perth on the lower postglacial terrace between fragments o and p (SI/C.11-18, Fig.5.2) showed sandy clay containing sand, gravel, and peat overlying silty sand (absent in SI/C.12), which in turn rests on gravel, the top of which varies in altitude between 0.0 and 2.8 m, and the base between -3.6 and -2.7 m in the 4 bores that penetrated into the underlying silty clay. The latter was proved down to at least -5.8 m O.D. Bore SI/C.1, at the edge of the Tay in Perth, showed made ground resting directly on the gravel layer, whose top and base are at -1.5 and -8.2 m respectively. Below the gravel are fine sands and clays down to -44.3 m O.D., beneath which is till resting on bedrock at -61.8 m.

The carseland stratigraphic sequence beneath Perth is similar to that revealed by the Friarton-Walnut Grove bores (Figs.5.2 & 5.4), which have already been discussed in relation to the buried gravel layer and underlying deposits (sec.1ci). The sub-carse peat rests directly on the gravel in some of the main carse bores of line B, as in some cases does the carse where the peat is absent, but a thin layer of grey silt sand intervenes in places. The sub-carse/sub-peat surface is relatively flat at an altitude ranging between 4.8 and 5.7 m over a distance of 450 m, suggesting the presence of an extensive buried terrace.

The stratigraphic sequence revealed in the lower Tay valley is the same as that in the lower Earn carselands (Chap.4).

CHAPTER SIX

AREA D - THE CARSE OF GOWRIE

Introduction

Area D extends 22 km from Inchyra in the southwest to Dundee in the northeast, and consists largely of the lowland tract, between the Sidlaw Hills and the Firth of Tay, known as the Carse of Gowrie. The field evidence is presented on three maps:

Figure 6.1, Inchyra to Pitroddie and Seaside;

Figure 6.2, Pitroddie and Powgavie to Snabs;

Figure 6.3, Castle Huntly to Dundee.

The Carse of Gowrie is made up largely of lateglacial and postglacial raised estuarine flats which, until the digging of deep drains or 'pows' in the 17th and 18th centuries, gave rise to extensive marshlands (Anon.,1797; Robertson,1799; Melville, 1935).

Protruding through these sandy and clayey flats are 'islands' of Old Red Sandstone veneered with till and fringed by higher raised beaches of lateglacial age. The largest of these 'islands' or 'inches', that on which Ardgaith and Errol are situated (Fig.6.1), rises well above the highest raised shoreline to an altitude of 48 m; and Middlebank (Fig.6.2) also has a summit projecting above the highest raised shoreline in

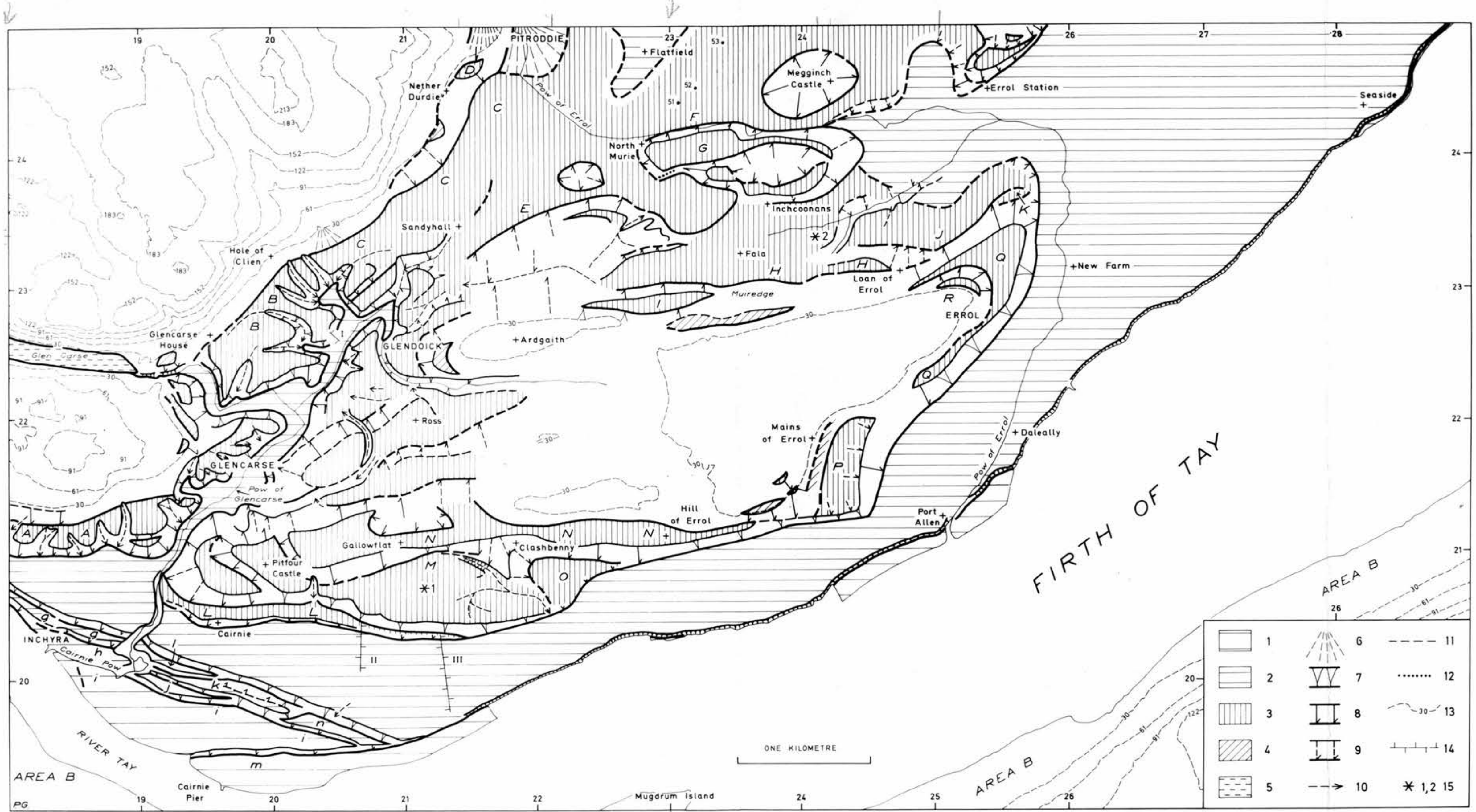


FIGURE 6.1 - Inchyra to Pitroddie and Seaside. 1. Lower postglacial flats; 2. Main carse; 3. Lateglacial estuarine flats; 4. Flats of unknown origin; 5. Lake flat; 6. Alluvial fan; 7-9. Steep, moderate, and gentle slopes; 10. Gully or dry valley; 11. Linear depression; 12. Ridge; 13. Contour (m O.D.); 14. Line of bores; 15. Claypits referred to in text. The numbered dots are positions of site investigation bores.

FIGURE 6.1 - Inchyra to Pitroddie and Seaside. 1. Lower postglacial fla
origin; 5. Lake flat; 6. Alluvial fan; 7-9. Steep, moderate, and gentle
13. Contour (m O.D.); 14. Line of bores; 15. Claypits referred to in te

POSITIONS OF SITE INVESTIGATION BORES

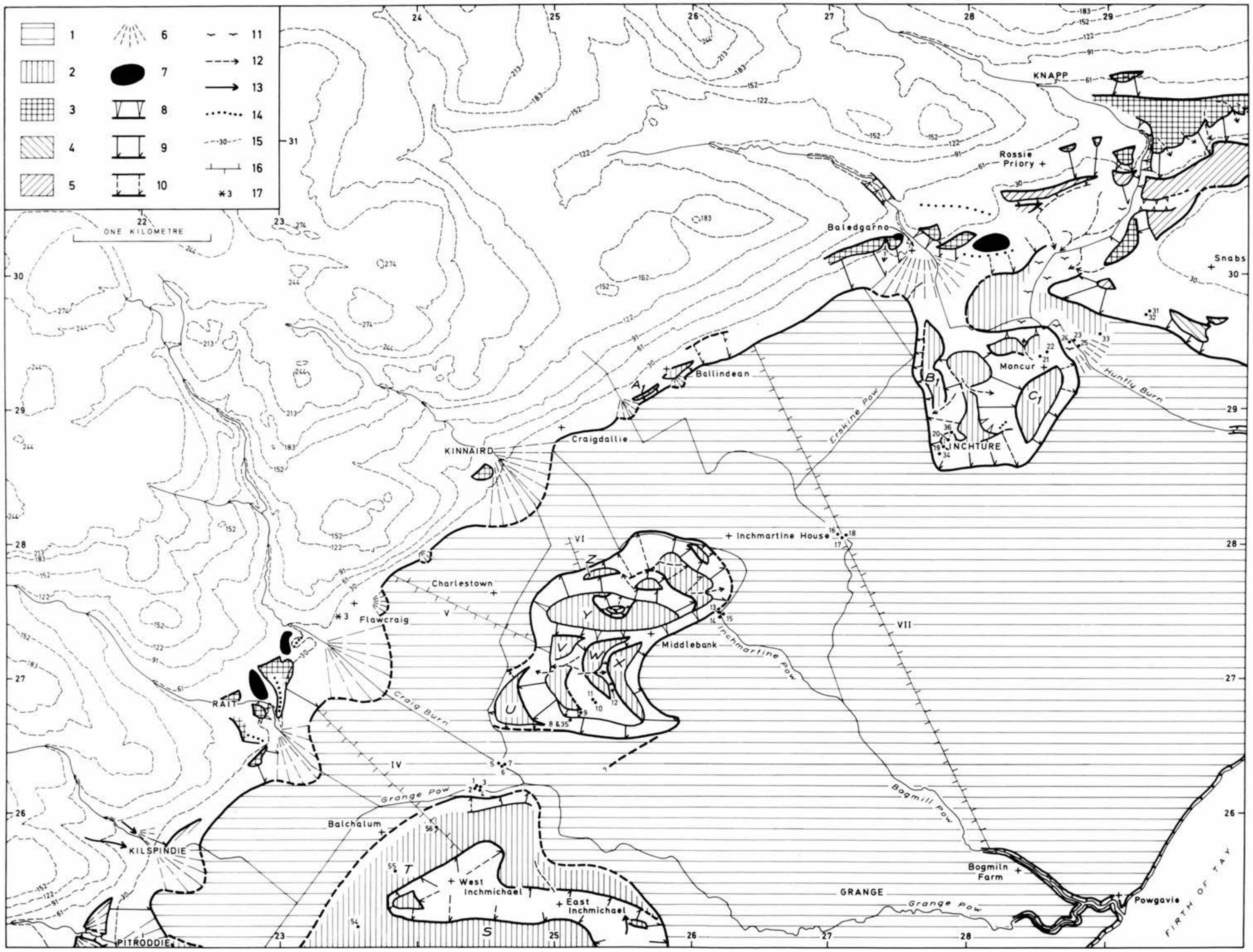


FIGURE 6.2 - Pitroddie and Powgavie to Snabs. 1. Main carse; 2. Lateglacial raised beach; 3. Fluvioglacial terrace; 4. Rock bench; 5. Step of unknown origin; 6. Alluvial fan; 7. Kettle; 8-10. Steep, moderate, and gentle slopes; 11. Alluvium; 12. Gully or dry valley; 13. Meltwater channel; 14. Ridge of sand & gravel; 15. Contour (m O.D.); 16. Line of bores; 17. Claypit referred to in text. The numbered dots are positions of site investigation bores.

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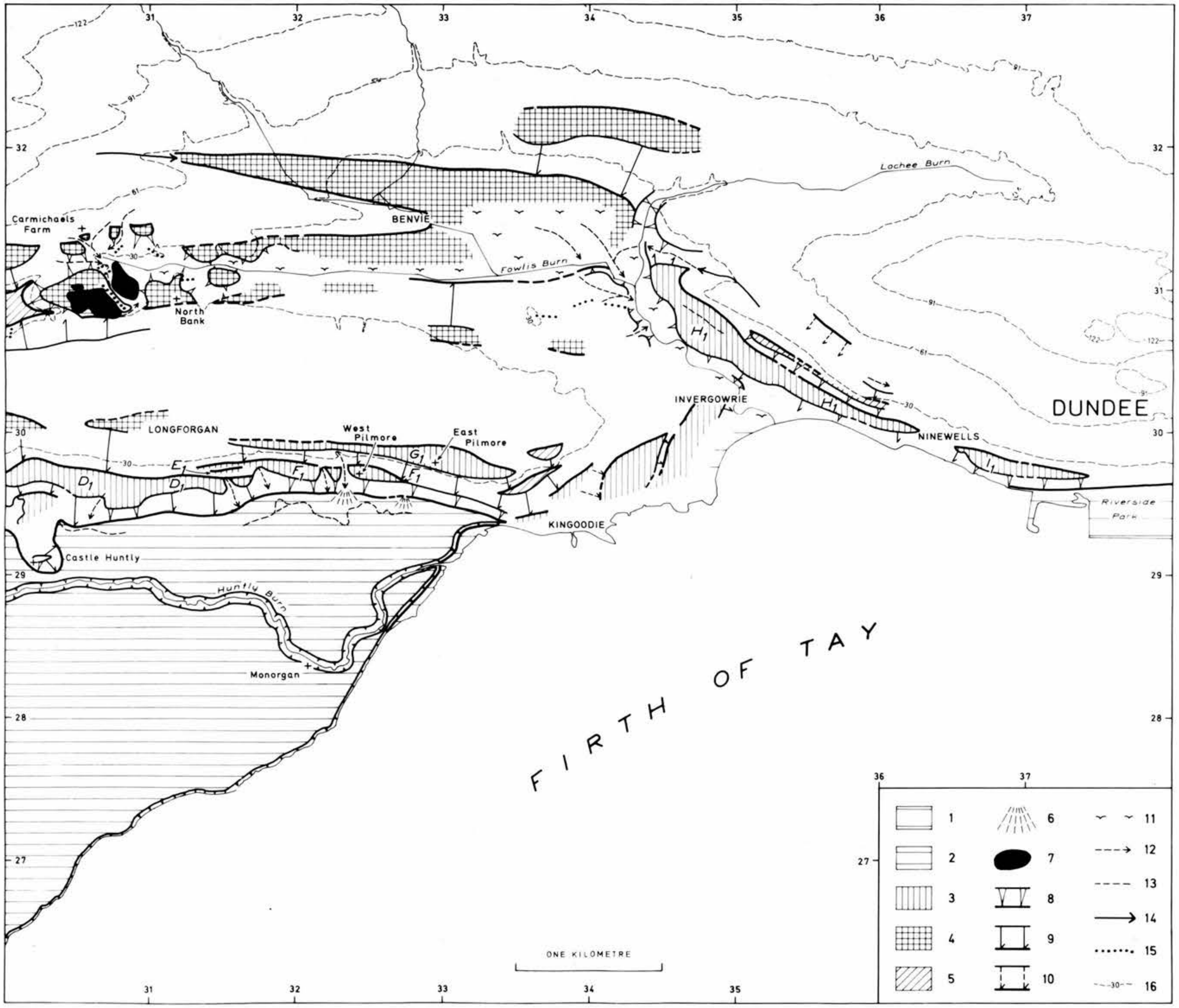


FIGURE 6.3 - Castle Huntly to Dundee. 1. Lower postglacial flat; 2. Main carse; 3. Lateglacial raised beach; 4. Fluvioglacial terrace; 5. Step of unknown origin; 6. Alluvial fan; 7. Kettle; 8-10. Steep, moderate, and gentle slopes; 11. Alluvium; 12. Gully or dry valley; 13. Linear depression; 14. Meltwater channel; 15. Ridge of sand & gravel; 16. Contour (m O.D.).

the vicinity. The other 'islands', including Megginch (Fig.6.1), Inchmichael, and Inchture (Fig.6.2), are much lower, and carry evidence of only the lower part of the lateglacial shoreline sequence.

The lower slopes of the Sidlaws contrast sharply with the 'islands' in that they bear only scant evidence of lateglacial raised shorelines, particularly between Pitroddie and Baledgarno (Fig.6.2). The bold slopes descend unbroken to the carselands along much of this stretch, which is also characterized by the presence of several large alluvial fans.

Fluvioglacial features are well developed only in the eastern part of the area, in the Baledgarno-Benvie depression (Figs.6.2 & 6.3).

As in Area B (Chap.4), the most extensive and most distinctive element in the area of raised estuarine flats is the carse, with which the following account therefore begins.

1. <u>The carselands</u>

a) <u>Surface form and extent</u>

The carselands of the Carse of Gowrie cover an area of about 40 sq.km, extending for 18 km in a southwest-northeast direction, with a maximal breadth of 5 km, and they form by far the greatest expanse of continuous raised beach in the Earn /Tay area. The general surface form is very similar to that of the lower Earn carselands (Chap.4), the main difference being the nature of the stream courses crossing the carse. In the Carse of Gowrie these are narrow artificial channels over much of their length, and even the largest stream, the Huntly Burn (Figs.6.2 & 6.3), owes much of its valley size to artificial excavation (Anon.,1797). The carselands of Area D, therefore, have even greater continuity than in Area B, and this is emphasized by the absence of terraces lower than the main carse, except in the Inchyra-Cairnie Pier area (Fig.6.1). Elsewhere the main carse is unbroken from the backslope to the steep, 8 or 9 m-high frontal cliff overlooking the present Tay saltmarshes, although at Port Allen, (Fig.6.1) and west of Kingoodie (Fig.6.3), small areas of reclaimed land lie at the cliff-foot. Before reclamation and other protective measures were taken, the carse cliff was subject to severe erosion, leading to rapid recession (Herdman,1792; Anon.,1797; Melville,1939).

The Main Postglacial Raised Shoreline backing the main carse is continuous all the way from west of Kinfauns in Area C (Fig.6.2) to Kingoodie (Fig.6.3), a west-east distance of 18 km, the actual distance along the shoreline being greatly in excess of this. It is clearly defined over much of its length, being backed by bluffs of varying heights fronting lateglacial raised beaches, or by steep hillslopes, but in the embayments near Megginch and at Flatfield (Fig.6.1) its inner margin is much less clear, and in the latter case could only be located by augering and levelling (sec.1d). The large alluvial fans mentioned above also obscure the shoreline in places. Between Glencarse and Glendoick the carse penetrates up the system of valleys and gullies that dissect the lateglacial raised beaches (Fig.6.1; sec.1d).

The lower postglacial terraces in the Inchyra-Cairnie Pier area form a staircase of 5 levels, the lowest of which (m, Fig. 6.1) is reclaimed land. Apart from i, which has a maximal width of 400 m, the terraces are narrow steps between 50 and 100 m wide. All are very flat, have steep frontal bluffs and backslopes, and are composed of grey silty clay similar to the main carse deposits.

b) Altitudinal data: the main carse level

The Main Postglacial Raised Shoreline was measured at 265 points, and the data are summarized in Table 6-1. Four sets of measurements, indicated by brackets in the table, must be viewed cautiously because of local influences on shoreline altitude. The 27 heights along the Kilspindie-Rait and Flawcraig-Kinnaird stretches of shoreline are high in relation to the rest of the shoreline, and the ground levels along lines of bores (IV & V, Figs. 6.2 & 6.4) show that in this area the carse surface as a whole is higher than usual. This probably results from the influx of alluvial material, as shown by the large fans, into a sheltered inlet. Similar reasoning applies to the 45 measurements along the Charlestown-Inchmartine and Ballindean-Inchture stretches, although the effect is less marked in these cases.

The means of the remaining 10 groups of measurements (totalling 193 altitude values) are, in order from southwest to northeast: 9.8 m, 9.7 m, 9.6 m, 9.6 m, 9.5 m, 9.8 m, 9.9 m, 9.9 m, 9.6 m, 9.3 m. These appear to indicate that the shore-

TABLE 6-1

THE MAIN POSTGLACIAL RAISED SHORELINE: CARSE OF COWRIE
(in order SW-NE)

Location	Altitude (m O.D.) range	Altitude (m O.D.) mean	No. of hts.	Dist. m	Reference numbers
*Tofthill - Glencarse	9.5-10.1	9.8	12	1,100	C.22;D.386-8,391-4, 398-401
Cairnie	9.5- 9.8	9.7	3	150	D.113,114,116
Gallowflat - Clashbenny	9.2- 9.8	9.6	24	1,900	D.134-50,267-73
Hill of Errol - Port Allen	9.4-10.1	9.6	25	1,900	D.219-37,282-7
Port Allen - West Leys	9.0-10.0	9.5	46	3,200	D.172-214,216-8
Errol Stn. - E. Inchmichael	9.7-10.0	9.8	14	1,000	D.797-810
(Kilspindie - Rait	10.4-11.0	10.6	12	600	D.620-4,626-32)
(Flawcraig - Kinnaird	10.5-11.0	10.7	15	700	D.633-47)
(Charlestown - Inchmartine	10.0-10.6	10.3	25	1,700	D.52-76)
Middlebank	9.8-10.2	9.9	15	1,100	D.88-102
(Ballindean - Inchture	9.8-10.5	10.1	20	2,700	D.4-10,12,19-27, 29-31)
Inchture - Moncur	9.7-10.1	9.9	19	1,300	D.288-306
Moncur - Castle Huntly	9.5- 9.8	9.6	11	800	D.312-22
Castle Huntly - Kingoodie	8.8- 9.7	9.3	24	2,150	D.327,328,333-54

TABLE 6-2

LOWER POSTGLACIAL SHORELINES: CARSE OF GOWRIE (in order W-E)

Location	Altitude (m O.D.) range	Altitude (m O.D.) mean	No. of hts.	Dist. m	Reference numbers
*g. Inchyra	6.2-6.6	6.4	13	1,100	C.386,387;D.719-23, 736-41
h. Inchyra	5.4-5.8	5.5	9	600	D.103-5,111,112, 724-7
i. Inchyra - Cairnie	3.1-3.5	3.4	25	1,950	D.107-10,762-9, 772-6,789-96
j. Cairnie	4.3-4.6	4.5	8	500	D.754-61
k. Cairnie	5.2-5.5	5.3	5	350	D.749-53
l. Cairnie	6.2-6.5	6.4	7	500	D.742-8
m. Cairnie	1.3-1.5	1.4	4	300	D.777,778,780,781
n. Cairnie	4.3-4.7	4.5	7	500	D.782-8

*These fragments continue into Area C.

( ) Brackets explained in Text.

line altitude successively falls, rises, then falls again, but on further analysis, it is clear that the direction of the shoreline is markedly oblique to that of the isobases, and the Area D data are not nearly so anomalous as they appear (Chap.9).

The shoreline data exhibit the usual high consistency of carse measurements, only 4 groups (totalling 115 measurements) having a range greater than 0.6 m. The maximal range of any group is 1.0 m, and that is by far the largest group, with 46 measurements over a distance of more than 3 km.

Levelled heights were also obtained along lines of bores running out from the back of the carse (Figs.6.1, 6.2 & 6.4). Of those lines that are long enough to be meaningful, III shows no overall gradient of the carse surface towards the Tay; IV and V, which cross an inlet, show no overall gradient, the former exhibiting a less regular carse surface than is usual; and VII shows an overall slope of just over 1 m in a distance of 4 km. The carse surface was also heighted in the Glencarse inlet; it rises from 9.8 m at the mouth of the inlet to about 10.8 m near its head, and the ground surface rises even higher to 11.3 m, at the extreme head of the inlet owing to the presence of surface peat over the carse (D.1-3, 365-7, Appendix I).

c) Altitudinal data: lower postglacial terraces

The height data obtained on the 8 lower postglacial terrace fragments are summarized in Table 6-2. The altitudes of the 5 levels in the staircase are as follows: 6.2-6.6 m (fragments g & l;

20 measurements), 5.2-5.8 m (h & k; 14 measurements), 4.3-4.7 m (j & n; 15 measurements), 3.1-3.5 m (i; 25 measurements), 1.3-1.5 m (m; 4 measurements). The lowest level is reclaimed land. As with the equivalent features in Areas B and C (Chaps. 4 & 5), the sharpness of the old shorelines and the steepness of the backslopes made measurement simple.

d) Stratigraphy and age relations

The former exposures along the cliffed front of the carse have long been overgrown, and there are no sections through the complete carse sequence that are known to the writer. The following account therefore relies on old descriptions and on the records of site investigation bores and the 75 bores sunk by the writer. The maps (Figs. 6.1 & 6.2) show the locations of site investigation bores and the writer's lines of bores (I-VII), and sections through the latter are shown in Figure 6.4. The sections along line I and through the Todd's Bridge bores (lines A & B, Figs.6.1 & 6.4) are discussed later (sec.2). The most valuable old accounts are the following: Anon.(1797), J.Smith (1839), Grierson (1845), Jamieson (1865), J.Geikie (1881a,1894), and Davidson (1939,1940).

The carse deposits, although generally similar to those previously described (Chap.4), include more silt and sand than in the Earn carselands, and a widespread though discontinuous layer of micaceous silty sand occurs in the parts nearest the Tay. This layer, about 1-1½ m above the peat, was reported all along the frontal cliff between Powgavie and Port Allen, and

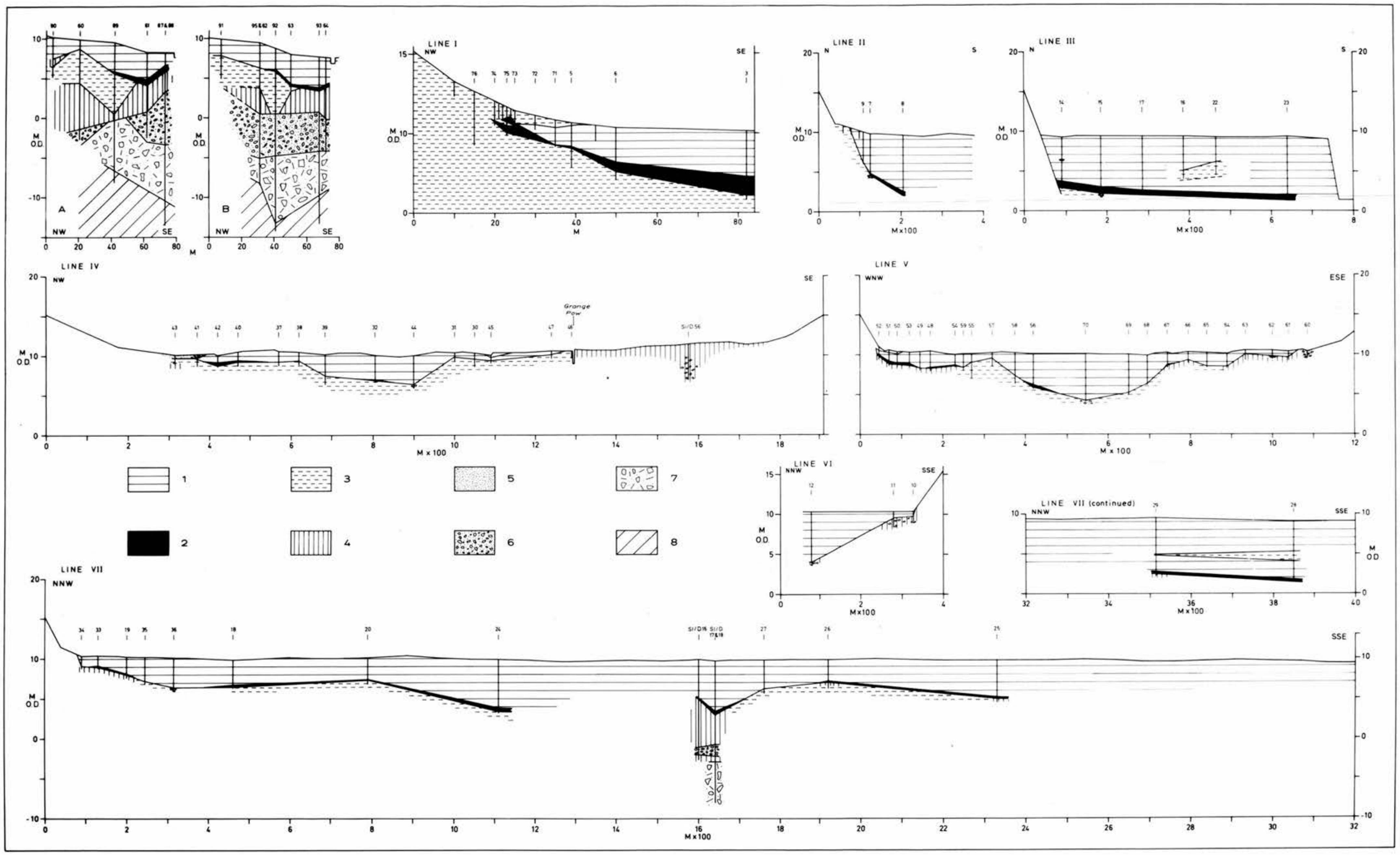


FIGURE 6.4 - Sections through lines of bores in the Carse of Gowrie. A and B are sections through the Todd's Bridge site investigation bores, and lines I to VII are the writer's lines of bores. 1. Carse deposits; 2. Peat; 3. Silty fine sand/ fine sandy silt; 4. Lateglacial clay (including laminated clay); 5. Medium & coarse sand; 6. Sand & gravel; 7. Till; 8. Bedrock.

near Monorgan, stretching inland for some distance, and containing cockle, mussel, and other littoral shells, particularly near Powgavie. The number of shells decreases westwards, none having been reported west of Errol. The writer encountered both the shelly and non-shelly facies of this layer, in lines VII (bores DB-28 & 29) and III (DB-14,16 & 22) respectively, and in 2 bores (DB-16 & 22) it was impenetrable with the equipment available. The origin of this layer is discussed later (Chap.9). Shells have been reported in the carse in many other eastern parts of the Carse of Gowrie, not always associated with silty sand, but they occur in localised lenticular beds rather than being widely distributed. The only bore not already mentioned in which the writer found shells was DB-36 (line VII).

The sub-carse peat is very widespread, and although sometimes thin and patchy between the 'islands' and the Sidlaws, where the carse is relatively thin (lines IV-VI), it is thick and continuous elsewhere. A thickness of 1.2 m was reported in the frontal cliff between Powgavie and Monorgan, and the greatest thickness penetrated by the writer's bores was 80 cm, though a thickness of 15-25 cm is more typical. The peat was impenetrable in bores DB-8,17,23, and 28 (lines II,III, & VII). The constituent materials are similar to those in the Earn carselands (Chaps. 4 & 5), although bones and deer's horns have also been found in it. There have been references to two peat layers in some places, including Dundee (Durham, 1903), but the second 'peat' is probably either a zone of more abundant plant remains than usual, as found in several of the writer's bores, or part of a drifted facies of the peat in which woody peat is interstratified with clay, as occurs west of Bridge of Earn (Chap.4) and in bore DB-23 (line III). A further possibility is that black organic matter sometimes found in the sub-peat material (e.g. DB-26, line VII) has been mistaken for a second peat layer. There is as yet no reliable evidence of separate buried peat beds one above the other.

The various materials on which the peat rests include the following:

(i) grey or brown micaceous fine sand, silty fine sand, or sandy silt;

(ii) tenacious pale blue micaceous clay or clayey silt;

(iii) stiff, dark red-brown clay or silt;

(iv) gravel, or sand and gravel.

The most common is (i), which is of similar appearance to the material of which several lateglacial raised beach fragments are composed. Deposit (ii) was located along lines V (DB-48 to 54,57) and VII (DB-18,19,25,26,29,33,34), (iii) along lines V (DB-61,63-66) and VI (DB-10, 11), and (iv) in lines II (DB-7), III (DB-15), V (DB-62,70), VI (DB-12), and VII (DB-36). The number and depth of penetration of bores are not yet sufficient to allow the significance of these different materials to be fully appreciated, but the few bores that penetrate more than one of these deposits suggest that (i) is overlain by (ii) (DB-25,26), and that (ii) either overlies (DB-67) or is interbedded with (iii) (DB-63,66). In one bore (DB-43), however, (i) overlies (ii). Deposit (iv) was encountered on the floors of buried channels in lines V-VII, and may therefore be fluvial, but its presence elsewhere cannot yet be accounted for.

The morphology of the buried surface is also somewhat variable (Fig.6.4). Line II, which is too short to reveal any buried terraces, shows a considerable depth of carse deposits close to the Main Postglacial Raised Shoreline, the frontal bluff of lateglacial raised beach fragment L plunging from about 10.6 to 4.6 m O.D. in a distance of 50 m. Line III shows a similar case, the depth of carse deposits about 50 m from the backslope being 5.6 m; it also suggests the presence of a buried terrace whose surface shelves towards the Tay, from about 2.5 m O.D. at the back to about 1.0 m at the front, these estimates being rather approximate because only the 2 innermost bores penetrated to the sub-peat surface.

Line IV, crossing the Balchalum carse inlet, shows thin carse clay and patchy sub-carse peat overlying a surface comprising two buried terraces separated by a 480 m-wide buried channel. The buried terrace northwest of the latter is 240 m wide and has a slight depression at the back of an otherwise flat surface at 9.3-9.4 m. The other step, less definite because of the dearth of bores, lies between 9.4 and about 10.0 m, and is more than 200 m across. The buried channel is probably the result of fluvial dissection near the large fans.

The material of the Craig Burn fan was shown by shallow (0.9 m-deep) augering to interdigitate with the carse deposits, suggesting that fan deposition continued well into postglacial times. The comparative irregularity of the carse surface along line IV partly reflects irregularities in the buried surface (Chap.9) and is partly due to dissection by streams flowing off the fans, leaving shallow dry channels, some of which are floored by a veneer of sand over the carse (e.g. DB-45).

Borehole DB-21 (NO 2365 2610), 230 m southwest of lone IV, showed a thin wedge (89 m) of carse clay overlain by 30 cm of sand and fine gravel, and resting on grey-brown micaceous clayey silt. Southwest of this point, shallow augering revealed a progressive thinning of the carse veneer over stiff yellowish-grey silt, the materials becoming intermingled at the surface between Oldwood and Flatfield. The point at which the carse deposits disappear, southwest of Flatfield, coincides with a change of level brought out by a line of heights running along the axis of the inlet (D.242-51,257-61,263-6, Appendix I), the carse-veneered surface lying at 10.8-11.2 m, and the surface of lateglacial raised beach fragment F at 12-12.5 m. The carse clay also feathers out towards the margins of the inlet, being mingled at the surface with the yellow silt in the area of the 'Main Postglacial' shoreline measurements between Kilspindie and Rait (Table 6-1), so that the latter may be regarded also as "buried shoreline" altitudes (Chap.8).

Line V, crossing the Charlestown inlet, shows an irregular buried surface that can be resolved into a fairly extensive buried terrace at 8.3-8.9 m on either side of a buried channel, which is more than 400 m wide, almost 6 m deep, and is immediately flanked by low ridges projecting 0.5-0.8 m above the buried terrace level. The origin of these ridges is a speculative matter; they might be levées, or they might be eroded remnants of a higher flat, the 100 m wide buried step at 9.7-10.0 m at the east-southeastern end of the section. Bores DB-50 to 52 show 0.3-0.4 m of sand and gravel overlyin carse deposits at the position of the Flawcraig-Kinnaird Main Postglacial shoreline heights (Table 6.1).

Line VI has only 3 bores and therefore reveals little, but it seems clear that the buried channel located in line V continues northeastwards between Middlebank and the hills, 6.3 m of carse being penetrated by bore DB-12 before it reached sand and gravel. The inner 2 bores (DB-10 & 11) reached a narrow buried step at 9.5-9.7 m.

The bores along line VII are mostly too far apart to throw much light on the form of the buried surface, except to indicate that it is not a simple series of buried steps descending seawards. The closely spaced inner bores show a narrow buried step at 9.0-9.1 m, and a shallow depression floored by sand and gravel, but the detailed form of the buried surface farther out remains to be determined; its altitude varies between about 1.5 and 7.3 m (bores DB-20,24-29; SI/D,16-18).

The site investigation bores of line VII (SI/D.16-18) revealed a gravel layer separating the immediate sub-peat materials from older lateglacial clays, as in other carseland bores, the altitudes of its top in each group of bores, in order from southwest to northeast, being as follows: Cairnie (1 bore: SI/D42,Fig.6.1), 1.5 m; Grange Pow (3 bores: SI/D.2-4,Fig.6.2), 0.9-1.2 m; Craig Burn (3 bores: SI/D.5-7, Fig.6.2), 0.0-0.5 m; Erskine Pow (3 bores: SI/D.16-18, line VII), -1.1 to -0.4 m. A buried gravel was also revealed by the Todd's Bridge (lines A & B, Figs.6.1 & 6.4) and Huntly Burn (SI/D.23-25,Fig.6.2) bores. In the former, the gravel rests on till and beneath the older lateglacial clays, and is therefore in a different stratigraphic position from that in the bores mentioned above. In the Huntly Burn bores, which were located on an alluvial fan, gravel occurs above and beneath the carse, and the buried gravel, whose top lies at 6.2-7.8 m, rests on bedrock at 4.2-4.8 m O.D., and is probably an earlier fan deposit. Of the 16 carseland bores not yet mentioned, 8 (SI/D.39-41, 65-69.Fig.6.1) were sunk in the Glencarse inlet, and are discussed later (sec.2); two (SI/D.1,33,Fig.6.2) failed to bottom the carse deposits; 4(SI/D.13-15,34,Fig.6.2) showed carse resting on bedrock at 7.3-8.3 m O.D.; and one (SI/D.57,Fig.6.1) penetrated only 0.5 m of the sub-peat material, the surface of which lies at 4.0 m O.D.

Unfortunately, none of the above 42 bores revealed the complete stratigraphic sequence down to bedrock, but there is no reason to believe that the carseland stratigraphic sequence in Area D is very different from that revealed by the more detailed borehole data in Areas B and C, and listed fully in Chapter 4.

2. Lateglacial raised beaches and shorelines

Lateglacial raised marine deposits occur at the surface over large tracts of the Carse of Gowrie, especially in the southwestern half of the area (Fig.6.1), where they occupy the depression between the Sidlaws and the Ardgaith-Errol 'island', and fringe the southern edge of the latter. Raised beaches also fringe the other carse 'islands' (Fig.6.2), and are well developed on the slopes backing the carse and the Tay between Castle Huntly and Dundee (Fig.6.3). They often occur in staircases of several features, and some of the shorelines are continuous over long distances. The height data, comprising 279 measurements along 35 shoreline fragments, are summarized in Table 6-3.

Fragment A is part of a raised beach, up to 250 m wide, that extends for 2½ km from Tofthill (Area C;Fig.5.2) to Glencarse (Fig.6.1), but owing to intensive gullying it could be measured only over a distance of 450 m, the altitude being 16.2-16.8 m (8 points). Some gullies cross the whole width of the beach, and some take the form of wide, bowl-like depressions. A section high on the frontal bluff (NO 1846 2104) revealed bedded micaceous fine sand, which forms the beach

TABLE 6-3

LATEGLACIAL RAISED SHORELINE FRAGMENTS: CARSE OF GOWRIE

Location	Altitude (m O.D.) range	Altitude (m O.D.) mean	No. of hts.	Dist. m	Reference numbers
A. Tofthill - Glencarse	16.2-16.8	16.5	8	450	D.403-7,409-11
(B. Glencarse House	19.4-20.1	19.6	4	500	D.379,380,382,383)
C. Glendoick - Pitroddie	14.6-16.1	15.2	27	1,500	D.584-94,596-610, 614
D. Nether Durdie	21.2-22.0	21.7	3	100	D.611-3
E. Sandyhall	13.4-14.1	13.7	16	800	D.568-83
F. North Murie	11.9-12.6	12.2	5	350	D.921-5
G. North Murie	14.0-14.6	14.2	4	250	D.238-41
H. Muiredge	16.2-16.5	16.3	5	950	D.368-71,402
(I. Muiredge	24.2-24.3	24.2	2	250	D.372,374)
J. Errol	11.2-11.9	11.6	11	900	D.154,155,506-14
(K. Errol	13.1-13.2	13.1	3	100	D.497-9)
L. Cairnie - Gallowflat	10.9-11.2	11.1	9	1,200	D.120-4, 130-3
M. Gallowflat	20.5-20.6	20.5	5	150	D.434-8
N. Gallowflat - Hill of Errol	24.5-25.6	25.1	32	2,050	D.424-33,449-67, 469-71
O. Clashbenny	11.6-12.1	11.8	9	400	D.439,440,442-8
P. Mains of Errol	23.8-24.4	24.0	7	300	D.475-81
Q. Errol	23.0-24.7	23.8	11	1,300	D.482-6,488-93
(R. Errol	27.1-27.5	27.2	3	100	D.494-6)
S. S.Inchmichael	11.8-12.4	12.0	10	800	D.717,718,728-35
T. W.Inchmichael	12.2-12.6	12.4	9	650	D.850-7,900
U. Middlebank	11.1-11.2	11.1	3	150	D.77-9
V. Middlebank	20.6-20.9	20.8	4	150	D.663-666
W. Middlebank	15.6-16.0	15.8	4	250	D.668-71
X. Middlebank	12.5-12.9	12.6	6	350	D.672-7
Y. Middlebank	23.4-24.0	23.7	7	350	D.648-54
Z. Middlebank	14.0-14.4	14.2	3	100	D.660-2
A_1 Ballindean	11.8-12.2	12.1	5	200	D.35-9
B_1 Inchture	12.8-12.9	12.9	5	200	D.679-83
C_1 Moncur	12.5-12.8	12.6	5	300	D.684,685,687-9
D_1 Longforgan	21.2-22.3	21.7	15	950	D.521-4,527,528, 530-7,542
E_1 Longforgan	25.2-25.7	25.4	3	100	D.538-40
F_1 West Pilmore	27.3-28.0	27.6	11	800	D.543,544,548-56
G_1 East Pilmore	31.6-32.1	31.8	8	350	D.560-7
H_1 Invergowrie - Ninewells	18.8-19.8	19.3	14	1,550	D.830,831,926-37
(I_1 Ninewells	19.6-19.9	19.7	3	150	D.375-7)

( ) Brackets explained in Text.

surface, overlying cross-bedded sand and fine gravel.

Fragments B,C,E to H,J,K,S, and T are components of an extensive area of lateglacial estuarine flats. Exposures and augering showed a surface composition of yellowish-brown or gray-brown micaceous silty fine sand in the southwestern parts of the flats, comprising fragment B and the southwestern part of C, but eastwards and northeastwards the surface material becomes finer, and is silty clay on the rest of fragment C, varies between fine sand and silty clay along fragment E, and is laminated silty clay and silty fine sand on fragments F,G,H,J,S, and T. Occasional small stones occur throughout the area. The records of 27 site investigation bores (SI/D.43,44,46-56,70-83,Figs.6.1 & 6.2) sunk on these flats show depths of between 4 and 12 m of such deposits, in most cases described as alternating clayey and fine sandy material. Bores SI/D.73-76, sunk in a valley crossing the flats (Fig.6.1), showed till beneath the marine deposits, bedrock being reached in 3 bores (SI/D.73-75), at 3.2-7.4 m O.D. Bore SI/D.45 showed a low mound protruding above the flats (Fig.6.1) to be composed of sand and gravel.

The laminated clay is known to be fossiliferous in the Fala-Inchcoonans area (Fig6.1), claypit exposures having been examined by T.Brown (1867) and Davidson (1932), who both described a highly arctic shell fauna. The section examined by Davidson (NO 2365 2340) revealed:

3. Yellowish brown sandy clay 2.5-3.0 m thick

2. Fine blue clay, coarsening upwards 1.5-2.1 m thick

1. Fine red clay over 1.2 m thick

and the most recent pit (*2,Fig.6.1) reveals a similar sequence, deposits 2 and 3 being varved and laminated. Each varve near the top of the section consists of 8-13 cm of blue-grey clay, 2-3 cm of red clay, and 2 cm of yellow sand, but the latter element becomes less conspicuous lower down. The colour difference between 2 and 3 as described by Davidson may well relate to conditions of moisture and aeration, for when the face (pit *2) is dug back, a distinction between the upper 2 layers is more readily made on grounds of particle size than of colour. The basal red clay is laminated, and rests on a layer of gravel, cobbles and boulders. Stones and boulders, often striated, are also scattered through all layers of the clay. The rich arctic estuarine fauna, which is in situ and is most abundant in the lower layers, "includes Musculus spp., Pecten groenlandica, Astarte borealis, Buccinum groenlandicum, Saxicava spp., over 20 species of ostracods and 4 species of Foraminifera" (A.R.MacGregor,1968, p.105). Bones of the common seal Phoca vitulina have also been found (Davidson,1935). A more temperate fauna including Mytilus and Ostrea has been found in the upper part of the clay, but the latter is not carse clay as assumed by MacGregor (loc.cit.), for apart from its great dissimilarity from the carse clay, its top lies at an altitude of 11.8 m (D.151-3,Appendix I), almost 2 m higher than the nearest carse. Other reported organic remains include drifted oak-wood which, despite its temperate character, was found in the lower beds of clay containing arctic shells (Davidson,1932).

Southwest of Sandyhall, the lateglacial estuarine flats are dissected by gullies and valleys, either dry or artificially drained. The bottoms of the larger valleys are flat, having been infilled by sub-carse peat and carse clay (Sissons, Cullingford and Smith,1965). 34 bores have been sunk on the floor and lower valleyside of the largest valley, between Glendoick and the open carselands, 12 by the writer(DB-1,2, & 4, Appendix II; & line I,Figs.6.1 & 6.4), and the remainder for site investigations (SI/D.39-41,59,65-69, & lines A & B Figs.6.1 & 6.4). All except some of the valleyside bores (line I) passed through 0.9-4.4 m of carse deposits resting in most cases on compact peat up to 1.4 m thick. Borehole DB-4, near the headward limit of the carse infill, showed 0.9 m of carse clay underlain by 1.4 m of peat, and overlain by 1.6 m of surface peat, this being one of the very few occurrences of surface peat over carse clay in the Earn-Tay basin (Chap.9). The immediate sub-peat material is mostly grey or brown fine sand or silty fine sand, similar in appearance to the pale grey or yellowish-grey fine sand that surfaces the lateglacial raised beaches in the vicinity. Line I shows the peat feathering out against the fine sand of the raised beach, and the carse deposits wedging out against the peat, both carse and peat being covered at the valleyside by sand that has moved downslope. The records of the Todd's

Bridge bores (lines A & B) describe a mixture of fine sand and laminated silty clay with sandy layers beneath the peat. There is no evidence of any deposit intervening between the late-glacial beach deposits and the peat, so it is concluded that the latter rests directly on the floor of a valley cut into the former (i.e. that the valley was not transgressed by the sea until carse times). The subject of pre-carse valleys and gullies will be discussed in a wider context later (Chap.8).

The surface of beach fragment B is very flat between the gullies, but the latter encroach upon the shoreline to such a degree that only 4 heights were measured, well out from the back-feature. They range between 19.4 and 20.1 m in a distance of 500 m.

Fragment C has a long, very sharp back-feature at the foot of the Sidlaws, 27 heights over a distance of 1.5 km ranging between 14.6 and 16.1 m. C is thus about $4\frac{1}{2}$ m lower than B, the break between them being obscured by gullies. A small, 100 m-wide terrace, D, perched on the backslope of C near the Pitroddie fans, has a shoreline altitude of 21.2-22.0 m (3 measurements in 100 m).

The shoreline of fragment E, across the flats from C, lies at 13.4-14.1 m (16 heights in 800 m), which is about 1.5 m lower than C. A morphological break is evident between the 2 levels, though it is partly obscured by dissection.

Fragment F has a sharp back-feature at 11.9-12.6 m (5 measurements in 350 m), and G, a 250 m-wide step above F, is backed by a clear shoreline at 14.0-14.6 m (4 heights in 250 m).

As a result of dissection, and of a back-feature that is vague in places, the 2 km-long shoreline of fragment H was measured at only 5 points in a distance of 950 m, 4 measurements being along the easternmost 300 m. The altitude is 16.2-16.5 m. About 8 m upslope from the western end of H lies fragment I, with a surface composition of silty fine sand and a rather gradual back-feature at 24.2-24.3 m (2 heights, 250 m apart).

Fragment J is separated from the eastern end of H by a gentle backslope, and a 400 m-stretch of shoreline is too vague to measure, but 11 heights in a total distance of 900 m range between 11.2 and 11.9 m. The morphological feature between the front of J and the carse is vague. About $1\frac{1}{2}$ m above the eastern end of J is a very small but clear terrace, K, whose back-feature was heighted as 13.1-13.2 m (3 points in 100 m).

Fragments S and T (Fig.6.2) are parts of one flat that almost encircles Inchmichael. Both measured stretches of shoreline are sharp, S lying at 11.8-12.4 m (10 heights in 800 m), and T at 12.2-12.6 m (9 heights in 650 m). The shoreline altitude of T was checked by 2 lines of levelled heights running perpendicular to the shoreline, the altitude and position of the latter in each case agreeing very closely with those previously determined by the usual means (Chap.2).

The lowest of the lateglacial raised beaches fringing the seaward edge of the Ardgaith-Errol 'island', L, is just above the carse, although morphologically and stratigraphically distinct from it.

L is up to 120 m wide, and is degraded at its eastern end, where it is crossed by bore lines II and III (Figs.6.1 & 6.4). Its shoreline altitude is 10.9-11.2 m (9 heights in 1.2 km), and its surface composition is grey-brown micaceous fine sand.

In a staircase above L are fragments M and N. The surface of M, over 1.5 km long and up to 500 m wide, has been extensively pitted by clay workings, including one pit (*1, Fig.6.1) that is still in use. The clay, about 3 m thick, shows similar lamination and banding to that at Inchcoonans (*2), and contains pulpy shell masses that cannot be separated from the clay. It also contains rootlets near the bottom, but these may be recent intrusions from a belt of trees that once grew on the site. The floor of the pit is strewn with erratic boulders of varied lithology, up to 1 m across and sometimes striated. Some of these are in situ, belonging to the gravel and boulder layer underlying the clay, but many have come from the clay, in which quite large boulders are common. The sharp back-feature was measured over a distance of only 150 m, because of the claypits, the altitude being 20.5-20.6 m (5 points).

N is the westernmost part of a very flat terrace that continues, apart from two 400 m gaps, for a distance of over 5 km, and includes fragments P and Q. The composition of N near Gallowflat is 0.5-1.0 m of fine to medium sand with gravel overlying bedrock, but near Hill of Errol, the surface material is laminated and banded micaceous silt. The clear shoreline lies at 24.5-25.6 m (32 heights in 2 km). P, which has a fairly pronounced seaward slope, has a shoreline altitude of 23.8-24.4 m (7 heights in 300 m), and that of Q, a conspicuous step up to 400 m across, is 23.0-24.7 m (11 heights in 1300 m). The surface material on Q is silty and contains stones. Above Q is a narrow step, R, which is partly built on, and lies at 27.1-27.5 m (3 heights in 100 m). It is too small for height measurements to give a reliable indication of origin, but it is regarded as possibly marine.

Fragment O occupies a small embayment backing the carse, and has a surface composition of fine sand with occasional small stones. Its shoreline altitude is 11.6-12.1 m (9 heights in 400 m).

6 measurable features (U-Z) occur on Middlebank (Fig.6.2). U is a small terrace fragment just above carse level, with a maximal breadth of over 200 m and a shoreline altitude of 11.1-11.2 m (3 heights in 150 m). Fragment V, overlooking U, is the second highest member of a staircase of 4 raised beaches, the others being W, X, and Y. V is gullied, but a 150 m stretch of clear shoreline was heighted at 4 points as 20.6-20.9 m. The shoreline altitudes of W and X are 15.6-16.0 m (4 heights in 250 m) and 12.5-12.9 m (6 heights in 350 m) respectively, both fragments having well-preserved flats and sharp back-features. Y, the highest and most extensive fragment on Middlebank, almost encircles the summit, and has a very sharp back-feature heighted at 7 points in 350 m as 23.4-24.0 m. Z is a small step overlooking the Charlestown carse inlet, at 14.C-14.4 m (3 heights in 100 m). Boreholes SI/D.8,9, and 35, at the front of fragment V, penetrated

3.0-4.6 m of sandy clay with stones. SI/D.10 and 11, on the crest of a ridge between V and W, showed a thin layer of sandy clay over gravel and till, and a road-cutting showed bedrock about 5 m down. SI/D.12, and the edge of fragment W, passed through 3.0 m of sandy clay and gravel.

Fragment A_1, a narrow step just above the carse, is the only measurable raised beach fragment at the foot of the Sidlaws between Pitroddie and Baledgarno (Fig.6.2). The altitude of its back-feature, measured at 5 points in 200 m, is 11.8-12.2 m.

The Inchture 'island' has a flat top at an altitude of 15.2-15.8 m, as shown by 2 O.S. bench marks and by the ground levels of bores SI/D.36,19, and 20. The latter 2 both penetrated 6.4 m of sand and gravel, which was not bottomed, and SI/D.36 showed 1.0 m of sandy clay and stones overlying 2.8 m of sand and gravel, beneath which is 2.2 m of clay, partly laminated, resting on sand and gravel and bedrock. The rockhead altitude is 7.9 m.

This mesa-like terrace is fringed by lower raised beach fragments, 2 of which, B_1 and C_1, were each measured at 5 points in 200 m, giving altitudes of 12.8-12.9 m and 12.5-12.8 m respectively.

Near Snabs are some steps of uncertain origin, and 2 that are shown by adjacent rock outcrops to be rock benches, although 2 nearby bores, SI/D.31 and 32, showed at least 2.7 m of sand and gravel over the bedrock. East of Snabs, the hillslope below Longforgan bears a staircase of 4 well defined raised beaches

(Fig.6.3). The shoreline of the lowest, D_1, lies at 21.2-22.3 m (15 heights in 950 m), and that of E_1, a very narrow feature, at 25.2-25.7 m (3 heights in 100 m). F_1, which is segmented by gullies, has a shoreline altitude of 27.3-28.0 m, (11 heights in 800 m), and the highest terrace, G_1, was heighted at 8 points in 350 m along the back-feature as 31.6-32.1 m.

The 2 remaining measured shoreline fragments, H_1 and I_1, are probably parts of one feature. H_1, a conspicuous terrace up to 300 m wide, has a sharp back-feature that was heighted at 14 points over more than 1.5 km, the altitude being 18.8-19.8 m. The terrace surface is slightly less regular than most of those that were measured farther west. I_1 has a marked seaward slope, and the shoreline is of marginal suitability for measurement; 3 heights in 150 m range between 19.6 and 19.9 m.

3. Fluvioglacial features

As mentioned earlier, fluvioglacial features are well developed only in the Baledgarno-Benvie depression (Figs.6.2 & 6.3), the most notable features farther west being the high-level terrace and fan remnants that lie above the main fans at Pitroddie, Kilspindie, Rait, Kinnaird, and Baledgarno. Most of these features lie at altitudes considerably greater than 30 m, and at Rait and Baledgarno (Fig.6.2) are associated with kettles and ice contact ridges. Two meltwater channels cut in rock flank the present river valley upstream of the Kilspindie fans, and the size and form of the river valleys along the southeastern edge of the Sidlaws suggest erosion by much larger rivers than those occupying them now.

A short distance east of Baledgarno is a distinct kettle fringed by a terrace and a ridge, both of fluvioglacial material. The lowest part of the kettle rim was not heighted, but it definitely lies below 27 m O.D. (O.S. spot height). Farther east are several scattered terrace fragments, probably fluvioglacial, at altitudes between about 25 m and 60 m, and a large gullied and kettled terrace. Although the latter could not be measured, it is clear from Ordnance Survey bench marks and spot heights that it slopes down steeply towards the east, from about 42 m near Knapp to about 37 m O.D. south of Carmichaels Farm, and down to less than 24 m at Benvie, where it appears to merge with a steeply inclined flat which in turn merges with the flat floor of a large meltwater channel. The surface composition is coarse sand, gravel, and cobbles. The terrace is highly fragmented near Carmichaels Farm by large kettles, and dead ice depressions containing small kames, and it is replaced eastwards by a lower, uneven alluvial spread.

The relevance of these features to shoreline displacement will be considered later (Chap.8).

CHAPTER SEVEN

THE ANALYSIS OF RAISED SHORELINE ALTITUDINAL DATA

Introduction

The previous four chapters have described the field evidence of raised beaches and shorelines, and related phenomena, and have included summaries of the altitudinal data obtained by the methods explained in Chapter 2. Chapters 8-10 are concerned with using this evidence to establish the pattern and nature of lateglacial and postglacial shoreline displacement. The purpose of the present chapter is to evaluate ways of analysing raised shoreline height data, and to describe the methods by which the shorelines postulated in Chapters 8 and 9 were identified.

A fundamental problem in raised shoreline studies is that, although one or two broadly synchronous shorelines can sometimes be identified over large areas on grounds of morphological continuity, stratigraphic distinctiveness, or both, most of the evidence is highly fragmented, and the basic requirement is a means of correlating the fragments. The two main groups of techniques for doing this are: (1) dating techniques, and (2) graphical methods involving the use of shoreline diagrams.

1. Dating techniques

An ideal way of correlating raised beach fragments would be to date them accurately, and thus be able to identify contemporaneous features. Unfortunately, it is very rare for raised beach deposits in an area consistently to contain material suitable for dating, whether by pollen analysis, radiocarbon assay, varve dating, or archaeological remains, and even where such materials do occur, there are several problems in relating them to specific shore levels. Nevertheless, several studies have relied heavily on such techniques.

a) Pollen analysis and microfaunal techniques

Workers in Fennoscandia have long used pollen analysis for studies of shoreline displacement, either irrespective of morphological evidence of raised shorelines (e.g. Hafsten,1959) or in conjunction with it (e.g. Sauramo,1958; Hyyppä,1963), the pollen stratigraphy being tied to one of the varve chronologies or to radiocarbon dates to give absolute age information. Hafsten, working in Oslofjord, dated the emergence of closed basins now containing bogs or small lakes by pollen and diatom analysis of the sediments, the change from saline to freshwater conditions being the feature that was dated, and the altitude of the basin threshold giving the relative sea level at the time of change. By studying 17 sites at a wide range of elevations, Hafsten was able to construct a curve of postglacial shoreline displacement. Sauramo and Hyyppä used a broadly similar dating technique in conjunction with the heighting of raised shoreline fragments to establish synchronous raised shore levels of the Baltic. Donner (1964) also used this technique, together with archaeological dating, to identify raised shoreline positions in part of Finland, having failed to identify clear shorelines from altitudinal data alone.

In eastern Scotland, opportunities for such techniques are almost non-existent, there being very few suitable sites within the more restricted altitudinal zone in which lateglacial and postglacial shoreline displacement has occurred. There is considerable scope, however, for pollen and microfaunal studies of raised estuarine sediments, and of terrestrial strata interbedded with them, and work on pollen dating is well under way in the Forth carselands (Newey,1966; Brooks,1972; Chap.9). This work applies at present only to the postglacial sequence, although it may have scope also in the dating of lateglacial sediments. However, such studies are of greatest value in conjunction with morphological work, so that dates obtained from a small number of sites have widespread relevance. Little microfloral or microfaunal work has yet been carried out in the Earn-Tay area (Chaps.4,5 & 9).

b) Radiocarbon dating

Radiocarbon dating of organic matter included in, or interbedded with, raised beach sediments can be used both for establishing an uplift curve for a locality and for correlating raised beach fragments. There are many examples of the former approach, including the work of Feyling-Hanssen and Olsson (1959), Olsson (1960), and Olsson and Blake (1961) in Spitsbergen, and Andrews (1968b,1970) in Arctic Canada, but opportunities for the latter approach are severely restricted in most places by the sporadic distribution of datable material. In work on raised shorelines (as distinct from work on uplift curves) radio-carbon dating is used mainly as an adjunct to graphical methods, each date being applied to a shoreline recognised with the aid of shoreline diagrams, and two or more dates on one shoreline help to test the validity of the correlation.

The usefulness of radiocarbon dating is limited by numerous sources of error, and meticulous care is necessary in selecting and obtaining a sample from the field if a meaningful date is to be obtained, as pointed out by Godwin (1951) and Barker (1958). An erroneous age can result from the inclusion in the sample of carbon-bearing materials of different age, too young an age being caused by, for example, growing roots, burrowing animals, water movement, and recent bacterial activity, and too old an age by the incorporation of inactive carbon, especially in limestone areas, or by the inclusion of organic material from older formations. The latter is an ever-present danger in the case of water-lain deposits, and is particularly acute in the case of shelly raised beaches, which may contain shells washed by wave action from the frontal bluff of a higher and older feature, and shells deposited offshore at a period of higher relative sea level and reworked as the littoral zone migrated across the former sea bottom. Reworking of older shells can also result from a transgression. Another problem with both shells and the inorganic fraction of bones is the danger that the calcium carbonate of the sample has been exchanged with dissolved carbonate in the groundwater, resulting in an age that is either too high or too low, but this can be minimised by removal in the laboratory of the outer parts of shell and bone samples. The special problems of dating shell and bone samples in shoreline displacement studies were discussed by Olsson and Blake (1961), who recommended the use only of thick shells without pitted surfaces. The problem of relating a shell sample to a particular relative sea level is illustrated by the fact that 6 shell samples collected at various elevations in Spitsbergen all gave roughly the same age (Olsson and Blake, 1961).

Because of these uncertainties, no attempts were made to date the shelly Main Postglacial Raised Beach in eastern Fife (Chap.3), despite the ease of sample collection. There is much less danger of including shells derived from older formations in the case of estuarine deposits containing localised beds or lenses of shells in situ, but repeated attempts to collect sufficient thick, coherent shell material for dating were unsuccessful at both the Inchcoonans and Gallowflat claypits (Chap.6). The only relevant radiocarbon dates in the Earn-Tay-East Fife area are of peat samples from near Leuchars, Carey, Eastfield of Dunbarney, and Broombarns (Chaps.3-5). A danger in the use of dates of such peat samples is the possibility of a hiatus in the stratigraphic record between the dated horizon and the underlying or overlying estuarine material. This effect can be minimised, as in the Forth (Sissons 1966, 1967a; Newey, 1966), by taking samples only where

where the transition from an estuarine to a terrestrial environment, or vice versa, has been recognised by pollen analysis. Unfortunately, there have been no pollen studies that are sufficiently detailed for this purpose in the Earn-Tay area.

The usefulness of radiocarbon dates as aids to the recognition of synchronous raised shorelines may also be limited by the measurement errors, which are reflected in the standard deviations of the dates. The importance of the standard deviations when comparing dates has been stressed by Barker (1958) and Andrews (1969a), a basic point being that if the difference between 2 ages is less than the standard deviation of the difference, the 2 ages are not significantly different; and even where the arithmetic difference between the ages is between 1 and 2 standard deviations, there is still a fairly high probability that the difference is due to chance. This means that in cases where shoreline displacement has been very rapid, dates on successive shorelines may not be significantly different. On the other hand, in cases of slow shoreline displacement, the slight diachroneity of all shorelines (Chap.10) may result in 2 ages with small standard deviations from different points along one shoreline being significantly different.

Finally, the relationship between radiocarbon and sidereal age is more complicated than was once assumed, because there have been long-term variations in the ^{14}C concentration of the ^{14}C exchange reservoir (Stuiver and Suess,1966). Fortunately these variations are probably world-wide, affecting samples of the same sidereal age to the same degree, so that radiocarbon chronology is internally consistent. The maximum deviation from the true age over the past 10,000 years is less than 800 years, radiocarbon dates corresponding with 5,000-10,000 years ago possibly being 600-800 years too young (Stuiver,1970).

c) Varve dating

Varve dating is best developed in Fennoscandia, where detailed chronologies of deglaciation and shoreline displacement were established by G. De Geer (1912,1940) in Sweden, and Sauramo (1918,1923) in Finland. De Geer's chronology was extended to modern times by Lidén (1938), allowing dates to be expressed in years B.P. or B.C., and the accuracy of the Swedish chronology has been largely confirmed by radiocarbon dating (e.g. Iversen, 1953; Tauber,1970). A discrepancy between the Swedish and Finnish time scales was resolved by E. Nilsson (1960). Varve dating is thus a valuable dating tool, particularly as the annual character of varves, doubted by some (e.g. Flint,1957), has been confirmed in North America by comparison with radiocarbon dating and dendrochronology (Stuiver,1970), but although varved estuarine sediments are common in the Earn-Tay area, the major research project that would be necessary to establish a chronology has not yet been attempted.

2. Graphical methods

It is clear from the above that dating techniques, although valuable in establishing uplift curves for single localities, are most effective for work on raised shoreline correlation when used in conjunction with other techniques, principally graphical methods. These involve the plotting of raised shoreline altitudes according to their spatial distribution, allowing the recognition of approximately synchronous shorelines. The graphs or shoreline diagrams are of 2 main types: (a) height-distance diagrams, and (b) relation diagrams. These graphs, of course, give only a 2-dimensional representation of raised shorelines; the 3-dimensional form of deformed shore levels is best portrayed by isobase maps, an isobase being a line along which the former shoreline lies at the same altitude above datum.

a) Shoreline height-distance diagrams

Shoreline height-distance diagrams, sometimes called 'equidistant' or 'strandline' diagrams, are graphs of shoreline altitudes above datum against the distances of the measured points from a given origin, and projected into a given vertical plane. The heights are plotted along the y axis, and the distances along the x axis. Marked alignments of points are assumed to represent former shorelines.

However abundant and accurate the data may be, this type of diagram has fundamental limitations, including the following:

(i) The height-distance relationships are valid only if the vertical plane of projection (the x axis) is aligned at right angles to the isobases. Major deviations from this alignment produce distortions that may lead to miscorrelations, especially where the vertical separation between successive shorelines is small.

(ii) Isobase curvature within the area of field data also causes distortions, because the place of projection can only be truly orthogonal to the isobases within a limited part of the area (E. Nilsson, 1953).

The most important advantages of the simple height-distance diagram are that it gives a true indication of the 2-dimensional shape and the gradient of deformed shorelines, and is not based on any assumptions regarding the nature of shoreline displacement (an important point in view of the preconceived ideas that have bedevilled Scottish raised shoreline studies in the past).

b) Shoreline relation diagrams

In shoreline relation diagrams, probably first used by Ramsay (1920), and subsequently developed by several Fennoscandian workers, including Tanner (1930), Sauramo (1934, 1958), Hyyppä (1937, 1963) and von Post (1947, 1952), the y axis is shoreline elevation above datum (as in height-distance diagrams), but the x axis is the elevation above datum of a shoreline used as a reference level, and plotted as a straight line. Each shoreline altitude is plotted in relation to the altitude of the reference level at the same locality. The 3-dimensional form of the reference level thus controls the relative positions on the diagram of all other shoreline measurements, the object being to avoid the limitations of the height-distance diagram, and to allow information from a very wide area to be plotted on the same diagram.

The relation diagram is based on the assumption that there is a direct proportional relationship between the altitudes of shorelines of different ages. It thus assumes that isobases of successive shorelines are everywhere parallel to each other, which requires that the centre of uplift has remained in the same position throughout the period of shoreline displacement being considered, and that no other irregularities have occurred in the displacement that might upset the parallelism.

Recently, doubts have grown concerning the validity of this assumption, and the use of relation diagrams has been heavily criticized by Marthinussen (1960), Donner (1965), Andersen (1965), and Sissons (1967c,1972). Even Tanner (1930) emphasized the magnitude of the assumption, and stressed that its validity should be tested by dating shorelines over a wide area. Nevertheless, Synge and Stephens (1966) used a relation diagram that included data from a large part of Scotland and Northern Ireland, whilst Andrews (1968b,1969b,1970) claimed that the similarity of form of 21 uplift curves from Arctic Canada shows that the assumption is valid, and that relation diagrams based on the generalized equations describing the form of such curves can be used in a way that potentially "rivals radiocarbon dating for accurately establishing late- and postglacial chronologies and relative sea-level movements in coastal, glaciated areas" (1969b,p.73).

The accuracy of a relation diagram is controlled not only by the validity of the underlying assumption, but also by the accuracy of measurement and the degree of synchroneity of the reference level, whether this be a well-marked raised shoreline heighted in the field, as in most cases, or a level deduced from uplift curves, as in the work of Andrews. Any errors in identifying or measuring a synchronous reference level will be transmitted to the rest of the data. Problems may therefore be caused by the slightly diachronous nature of raised shorelines, because the degree of diachroneity varies between different shorelines according to the rate of displacement at the time of formation (Chap. 10). The diachroneity of the most commonly used reference level in Fennoscandia is sufficiently marked to have been clearly demonstrated by dating techniques (e.g. Ramsay, 1921,1924; Hyyppä,1937; Donner,1964).

3. Methods of analysis used in this study

a) Shoreline diagrams

The writer holds the view that the assumption on which the shoreline relation diagram is based is not justified in the present state of knowledge, and that the type of displacement involved requires to be demonstrated rather than assumed. The assumption may possibly be valid for some areas, but it is more reasonable to allow for the possibility of a changing centre (or centres) of uplift, and of changes in deformation geometry from other causes, that to assume the reverse. The diagrams in the following chapters (8-10) are therefore all of the height-distance or equidistant type, and are hereafter referred to simply as shoreline diagrams.

The problem of ensuring an orthogonal relationship of the vertical plane of projection to the isobases was eased by the presence of 2 widespread, well developed, and readily identified raised shorelines for which isobases could be drawn: the late-glacial Main Perth Raised Shoreline, and the Main Postglacial Raised Shoreline. Isobases were drawn for each of these shorelines, both for the Earn-Tay area and for the Earn-Tay and Forth areas together, using trend surface analysis. The Fortran IV computer program used for the latter produces maps of linear, quadratic, and cubic surfaces, and was originally derived from Whitten's (1963) surface-fitting program and a map-drawing program by P. Kahn, although it has been extensively modified by F. Nex, J. Drew, J. Coate, and the writer. Different planes of projection were used according to the relavant isobase direction, the distances of the measured points in each place being calculated from the National Grid eastings and northings by trigonometry, using a computer program written by V. Gardiner.

Errors arising from isobase curvature are very slight in the relatively small area studied, as shown by the trend surfaces calculated for the shorelines mentioned above: the quadratic and cubic surfaces show only slight curvature within the Earn-Tay area, and the very high proportion of the sums of squares accounted for by the linear surfaces (Chaps. 8 & 9) confirms the adequacy of the latter for isobase depiction in this area, although not always for the Earn-Tay and Forth areas together (Chaps. 9 & 10).

b) Identification of shorelines from the diagrams

As stated earlier, shorelines are usually identified on the basis of marked alignments of points on shoreline diagrams, and they are usually depicted as straight lines, despite the long-established curvilinear nature of shoreline deformation (J.W. Goldthwait,1908; Robinson,1908; Leverett & Taylor,1915; Ramsay,1924; Broecker,1966). Although a slight westward increase in gradient occurs along the Main Perth and Main Postglacial raised shorelines (Chaps. 8 & 9), they plot as almost straight lines on the diagrams, the area studied being too small for any marked curvilinearity to be apparent. The recognition of straight alignments is therefore a reasonable approach to the problem of correlation, particularly in view of the dearth of dating information. The method of measurement adopted is well suited to this purpose, and also enables curvilinear arrays, such as the lowest Earn river terrace, to be recognised on the diagrams (Chaps. 2 & 9).

It would be dangerous, however, to simply identify the most closely aligned arrays of dots on the diagrams, without regard to the following all-important constraints imposed by the field evidence:

(i) The staircase constraint. Clearly, raised beaches that occur one above the other in a staircase cannot be contemporaneous with each other. As shown in Chapters 3 to 6, both separate and overlapping staircases are frequent, and impose a valuable limit to the number of possible correlations.

(ii) The continuity constraint. Morphological continuity is often greater than the distribution of measured heights might suggest; some measured shoreline fragments are connected by a clear shoreline and/or terrace that for some reason could not be measured, and are clearly contemporaneous. Several examples were described in previous chapters.

(iii) The ice-margin constraint. Where a raised shoreline remnant was formed near a specific ice-margin position, it is obviously unrealistic to correlate it with features that lie in the area that was then ice-covered.

In the following chapters (8 & 9), these field constraints are indicated both in the text and on the shoreline diagrams (except where the symbols would obliterate the data points). Composition was not in general regarded as a reliable correlative aid because of facies changes, and, in some parts of the area, a general similarity of composition between features of different ages.

The gradients of the raised shorelines were calculated by linear regression analysis, using a computer program written by Till (1969), and corrected by V. Gardiner and the writer. It should be emphasized that regression analysis was used purely as an objective way of calculating shoreline gradients, and that the correlation coefficients merely express the closeness of fit, and do not relate to the validity of the correlations, which are based on visual inspection of shoreline diagrams in the light of the field constraints. Similarly, trend surface analysis was used as a means of constructing best-fit isobases, and the level of explanation expresses the closeness of fit, not the validity of the shoreline. All of the regression lines and surfaces fit the data very closely, and are statistically significant at the 99.9% level, but these high values result partly from the irregular distribution of the field data in clusters, and cannot be used to support the validity of the shorelines; it is possible to calculate least-squares lines and surfaces that fit the data very closely, and are significant at a very high level, but which are at variance with the field constraints and therefore cannot be valid raised shorelines.

CHAPTER EIGHT

LATEGLACIAL RAISED SHORELINES AND RELATED FEATURES

Introduction

This chapter deals with the lateglacial raised shorelines identified in the Earn-Tay area and eastern Fife, and discusses their relationships with other lateglacial events, and with the shoreline sequence in the Forth area. Certain general characteristics of the lateglacial raised beaches are also considered.

1. The East Fife raised shorelines formed before the Perth Readvance

a) The raised shorelines

The promontory of eastern Fife was the first part of the Earn-Tay and East Fife area to be freed of glacier ice during the period of deglaciation that followed the Aberdeen-Lammermuir Readvance (Sissons, 1965,1967 a and b), and it therefore bears evidence of the earliest raised shorelines. The altitudinal evidence for Area A was analysed initially on a shoreline diagram constructed in a WNW-ESE plane of projection (Fig.8.1), which was chosen as a starting point in the analysis because other evidence, principally a comparison of the height values along the Main Perth Raised Shoreline in the Tay-Forth region (sec.3a), suggested that a vertical plane at right angles to the isobases would not be many degrees off such an alignment. Diagrams constructed for W-E and NW-SE planes suggested the same correlations as those derived from Figure 8.1; only the shoreline gradients were slightly different.

This similarity of interpretation of diagrams constructed in different planes aligned between W-E and NW-SE results partly from the general WNW-ESE alignment of the coast of Area A (Figs.1.2 and 8.3), which means that the relative positions of the shoreline fragments do not change much in the different planes used, and partly from the nature of the field constraints, which limit the number of possible correlations to the point where changes in the plane of projection, within reasonable limits, make little difference to the interpretation. The field constraints for Area A (Tables 3-2 & 3-4) may be expressed schematically as follows:

$$\begin{array}{cccccccccccccccccccccccccc}
E & & & & & & & & Q & , & R \\
- & & & & & & & & - & & - \\
D & & (F) & & J & & (K) & & P & & P & & V & & Z & & Z & & B_1 & &))D_1 \\
- & & - & & - & & - & & - & & - & & & & - & & - & & - & & - \\
C & , & D & , & I & , & O & , & O & - & T & , & U & , & Y & , & Y & , & A_1 & , & C_1 & , & E_1 & , & F_1 & , \\
- & & & & - & & & & - & - & - & & & & - & & - \\
B & & & & H & & & & N & - & S & & & & W & & X \\
- & & & & - & & & & - & & & & & & - \\
A & & & & G & & & & M & & & & & & U \\
 & & & & & & & & - \\
 & & & & & & & & L
\end{array}$$

$$\begin{array}{cccccccc}
 & & (L_1) \\
 & & - \\
 & & K_1 \\
 & & - \\
H_1 & & J_1 & & & & & , (P_1),))Q_1 - R_1 \\
- & & - \\
G_1 & - & I_1 & - & N_1 & - & O_1 \\
 & & - & - & - \\
 & & & M_1
\end{array}$$

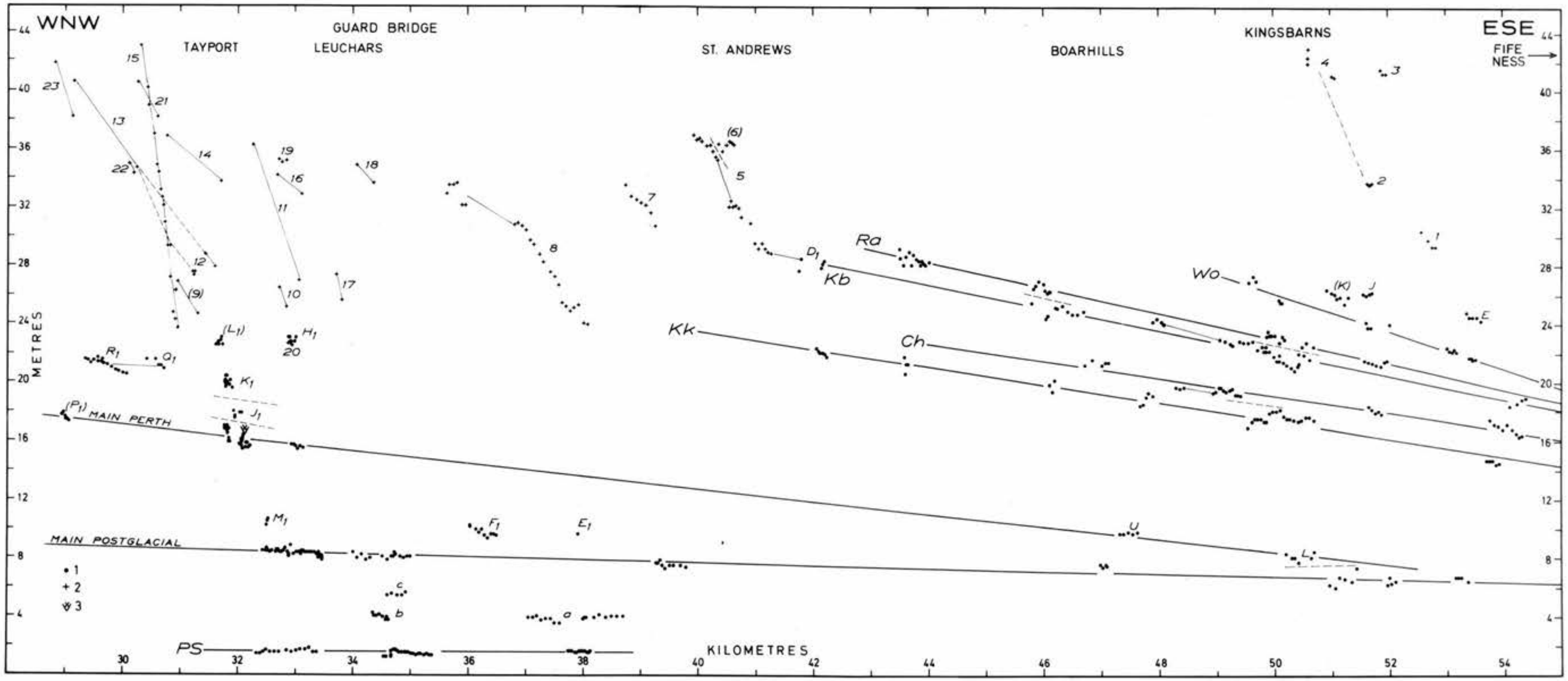


FIGURE 8.1 - Shoreline diagram, Area A: WNW-ESE plane. 1. Raised shoreline heights; 2. Fluvioglacial terrace heights; 3. Kettle rim height. Details of best-fit lines: Wormistone Shoreline (Wo), N=19, Y=91.1746-1.3003X, r=-0.9855; Randerston Shoreline (Ra), N=40, Y=66.5740-0.8706X, r=-0.9958; Kingsbarns Shoreline (Kb), N=51, Y=61.4134-0.7878X, r=-0.9844; Chesterhill Shoreline (Ch), N=33, Y=48.6707-0.5914X, r=-0.9792; Kinkell Shoreline (Kk), N=43, Y=48.0374-0.6122X, r=-0.9832; Main Perth, N=44, Y=29.9793-0.4314X, r=-0.9947; Main Postglacial, N=86, Y=11.4237-0.0932X, r=-0.9386. PS= present-day shoreline, line estimated.

(The meaningsof the symbols used in this and subsequent lists of field constraints are explained by the following examples:

$\frac{V}{U}$: fragment V occurs above U in a staircase

O – T: fragments O and T are morphologically continuous

))D_1: fragment D_1 is contemporaneous with a specific former ice-margin position

(F) : the measurements on fragment F are of doubtful value for shoreline height analysis).

Inspection of the shoreline diagram (Fig.8.1) in the light of these constraints reveals striking alignments of heights that suggest the presence of former shorelines. The Main Perth Raised Shoreline (fragments L,U,G_1,I_1,N_1,O_1, & P_1), and lower lateglacial features (fragments E_1,F_1, & M_1) will be considered later (sec.3). All of the lowest heights above the Main Perth Raised Shoreline east of St. Andrews are closely aligned and they define a former shoreline, here termed the <u>Kinkell Shoreline</u>, that slopes down towards ESE from about 22 m O.D. just east of St. Andrews to 14½ m at Fife Ness, a distance of almost 12 km. It includes fragments A,M,V,X,A_1, and C_1. The best-fit line calculated for the 43 measurements has a gradient of 0.61 m/km (regression details for this and all other best-fit lines are given in the captions to the shoreline diagrams). About 1½ m above the Kinkell Shoreline a line of measurements defines the <u>Chesterhill Shoreline</u>, which includes fragments B,G,N,S, and W, and slopes down from about 21½ m near Boarhills to 17 m at Fife Ness, a distance of 7 km. The best-fit line through the 33 measurements has a gradient of

0.59 m/km.

Above the two lowest shorelines the measurements fall into two particularly impressive linear arrays, the lower of which slopes down from 28 m at St. Andrews to 18½ m at Fife Ness, a distance of 12 km, and includes fragments C,O,T,Y, and D_1 (51 heights). It is here termed the Kingsbarns Shoreline, and its gradient is 0.79 m/km. Only 1–1½ m higher is the Randerston Shoreline, which includes fragments H,P,Z, and B_1 (40 heights) and slopes down from about 28½ m at Kinkell Ness to 21½ m at Randerston, a distance of 8 km, at a gradient of 0.87 m/km.

The evidence of raised shorelines above the Randerston Shoreline is less conclusive and is confined to the eastern part of the area within about 5 km of Fife Ness. The lowest of the remaining groups of heights are distinctly aligned, however, and they probably represent a fifth shoreline, the Wormistone Shoreline, comprising fragments D,I,Q, and R (19 heights). This feature slopes down from about 27 m to 21½ m in 4 km at a calculated gradient of 1.30 m/km.

The 19 heights still unaccounted for were obtained on 4 fragments, E,F,J, and K, of which one (F) may well be a structural bench (Chap.3).

Northwest of Guard Bridge 3 later stages in the pre-Perth Readvance shoreline displacement are indicated by fragments H_1 and L_1, K_1 and Q_1-R_1, and J_1 respectively (Fig.8.1).

On the south coast of eastern Fife (D.E.Smith, 1965; Cullingford & Smith, 1966), the lateglacial raised shorelines are much more fragmented than those of the north coast (Area A), and the resulting difficulties of correlation are aggravated by the direction of the coastline, which has a SW-NE orientation between Elie and Fife Ness (Fig. 1.2) and is therefore oblique to the probable general trend of the isobases. The effect of this is to make the alignment of the plane into which the measurements are projected somewhat critical, and different planes of projection produce appreciable differences in the relative positions of the measurements on the shoreline diagrams. Of the 3 planes that were tried initially (W-E, WNW-ESE, & NW-SE), the one that most readily produced alignments of heights suggesting former shorelines was also the one most likely to be near the true direction of displacement as interpreted from other evidence : WNW-ESE.

It was found possible to suggest two schemes for correlating the south coast fragments that obey the field constraints and give close alignments, Scheme A involving 6 shorelines with gradients of between 0.27 and 1.30 m/km, and Scheme B involving 5 shorelines with gradients of 0.68 to 1.30 m/km. The highest 2 shorelines are common to both schemes. Scheme A is clearly incompatible with the sequence on the north coast, because, excluding the highest 2 features, it involves shoreline gradients that are only about half as steep as those shown on Figure 8.1, but Scheme B is in remarkably close agreement with the latter, as shown by Figure 8.2, in which the two sets of lines are plotted together. The only serious anomaly is the large difference in gradient between Shoreline 2 and the Wormistone Shoreline: the B.3 and Kingsbarns,

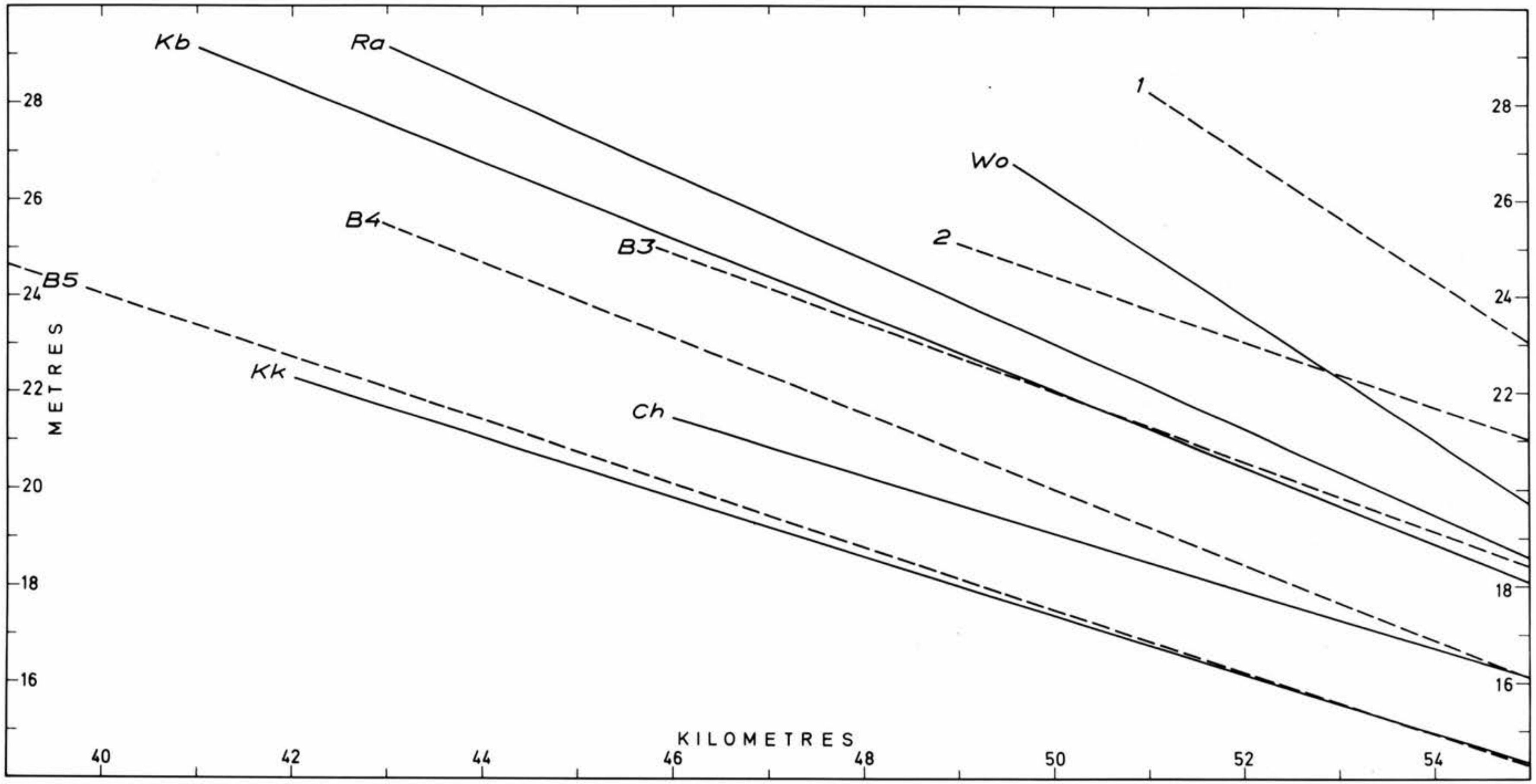


FIGURE 8.2 - Best-fit lines of the Area A and Area F (scheme B) shorelines: WNW-ESE plane.

and the B.5 and Kinkell, shorelines coincide almost exactly in both position and gradient. This close correspondence suggests that Scheme B is more likely to be valid that Scheme A.

The recognition of contemporaneous shorelines on both sides of the East Fife promontory allows the construction of isobases in order to determine more precisely the probable direction of shoreline tilting. Originally, the isobases for the Kinkell-B.5 shoreline, on which the evidence on both coasts together is most abundant, were determined by combining the results of linear regression analyses, each isobase connecting the points on the two coasts at which the raised shoreline could be said to lie at the specified average altitude (Cullingford & Smith, 1966). The direction of slope at right angles to the isobases was found to be down towards E18°S. This result is in close agreement with that given by trend-surface analysis for the same shoreline, the linear surface sloping down towards E19°S; and the mean of the directions of slope of the linear surfaces for the Kingsbarns-B.3, Chesterhill-B.4, and Kinkell-B.5 shorelines is E18°S (the individual directions being E23°S, E13°S, & E19°S respectively; Fig.8.3). A plane of projection aligned W18°N-E18°S is therefore confirmed as the most suitable in which to plot the lateglacial raised shoreline data from both sides of the promontory together.

In the shoreline diagram constructed in this plane (Fig.8.4), the data again fall into very distinct lines, and the only real anomaly suggested by the initial comparison of the two coasts

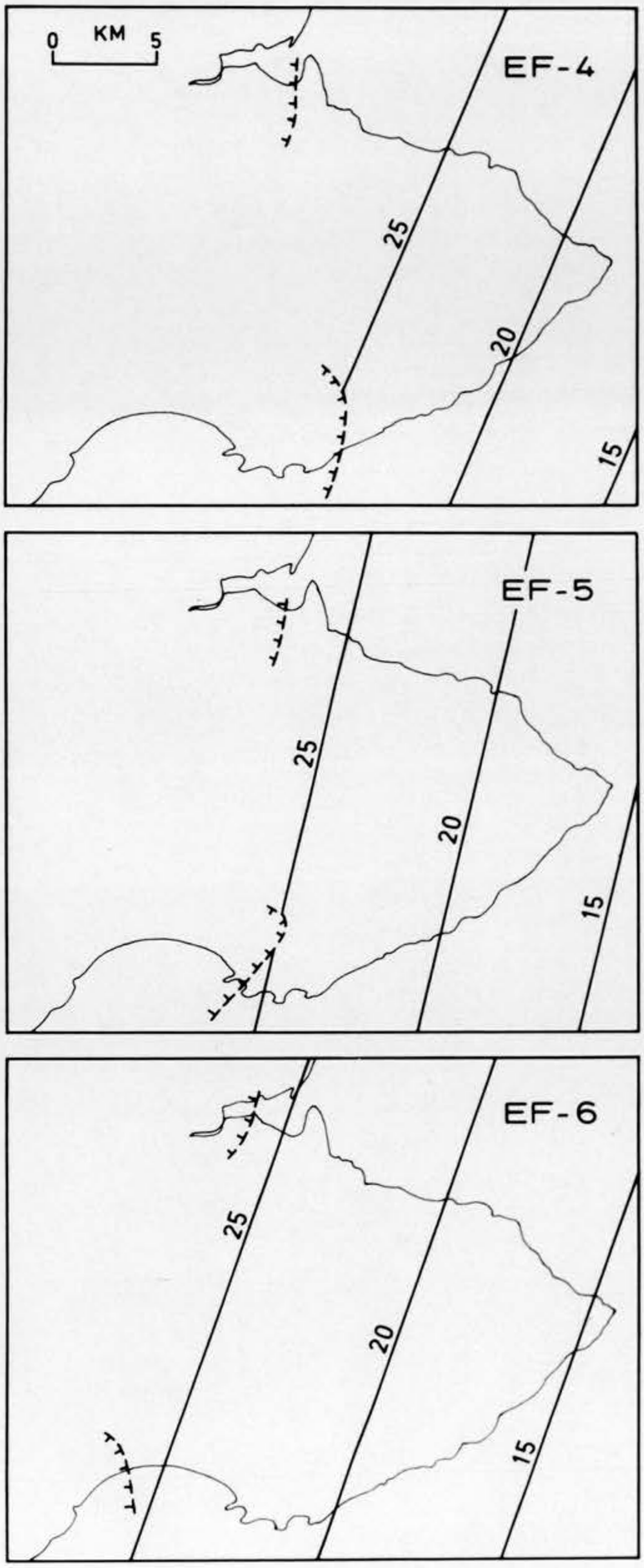


FIGURE 8.3 - Isobases of Shorelines EF-4 to EF-6, with approximate contemporary ice-margin positions.

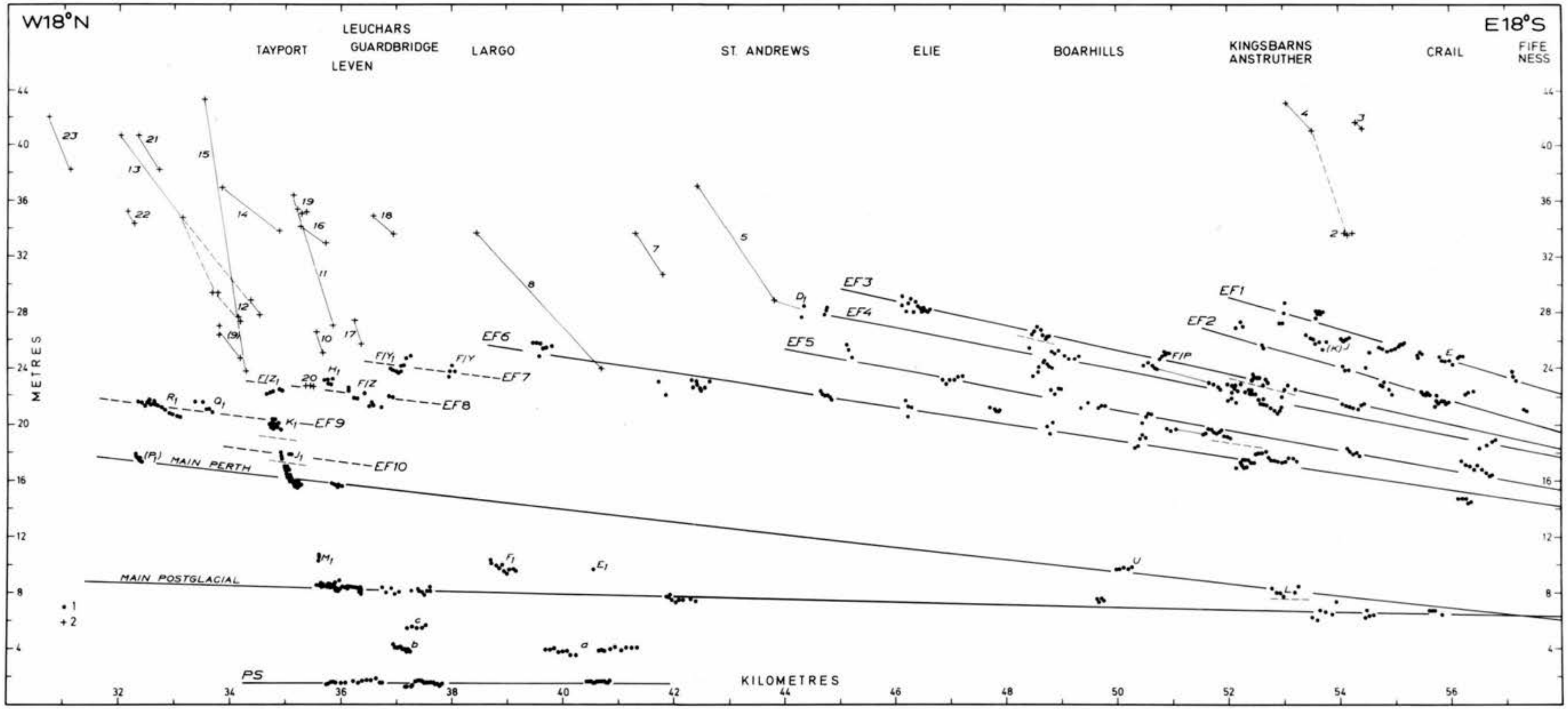


FIGURE 8.4 - Shoreline diagram, Areas A & F: W18^{O}N-E18^{O}S plane. 1. Raised shoreline heights; 2. Fluvioglacial terrace heights. Details of best-fit lines: EF-1, N=38, Y=89.0251-1.1517X, r=-0.9362; EF-2, N=35, Y=86.5780-1.1567X, r=-0.9474; EF-3, N=46, Y=69.2253-0.8778X, r=-0.9931; EF-4, N=61, Y=62.0433-0.7630X, r=-0.9700; EF-5, N=50, Y=57.1237-0.7204X, r=-0.9827; EF-6, N=69, Y=48.5609-0.5926X, r=-0.9828; Main Perth, N=44, Y=31.6769-0.4425X, r=-0.9942; Main Postglacial, N=86, Y=11.7665-0.0952X, r=-0.9359. PS= present-day shoreline.

(Fig.8.2), that of Shoreline 2, is now explained by the fact that one of the fragments originally assigned to Shoreline 2 appears to belong to the Randerston Shoreline, the rest of Shoreline 2 falling closely into line with the Wormistone Shoreline. Fragment E, uncorrelated on the north coast diagram (Fig.8.1), falls exactly on the line of Shoreline 1, and only F (probably structural), J, and K remain uncorrelated in the joint scheme.

Table 8-1 shows the north coast and south coast (Scheme B) components of the 6 principal pre-Perth Readvance shorelines of eastern Fife, which are designated EF-1 to EF-6. The gradients and closeness of fit of the best-fit lines in the W18°N-E18°S plane, and the directions of slope, gradients, and closeness of fit of the best-fit linear surfaces, are given in Table 8-2.

TABLE 8-1

Shoreline	North Coast	South Coast (Scheme B)
EF-1	Fragment E	Shoreline 1
EF-2	Wormistone Shoreline	Shoreline 2 except fragment F/P
EF-3	Randerston Shoreline	Fragment F/P
EF-4	Kingsbarns Shoreline	Shoreline B.3
EF-5	Chesterhill Shoreline	Shoreline B.4
EF-6	Kinkell Shoreline	Shoreline B.5

Table 8-2

Shoreline	N	Best-fit line in $W18^{o}N$-$E18^{o}S$ plane		Linear trend surface		
		Gradient m/km	r	Direction of slope down	Gradient m/km	%SS
EF-1	38	1.15	-0.936	$E18^{o}S$	1.16	88.10
EF-2	35	1.16	-0.947	$E25^{o}S$	1.10	92.56
EF-3	46	0.88	-0.993	$E15^{o}S$	0.89	99.12
EF-4	61	0.76	-0.970	$E23^{o}S$	0.77	96.00
EF-5	50	0.72	-0.983	$E13^{o}S$	0.65	97.87
EF-6	69	0.59	-0.983	$E19^{o}S$	0.61	96.70

It is clear from Table 8-2 that successively younger and lower shorelines have progressively lower gradients.

There is evidence north of Leuchars and in the western part of Largo Bay of 4 later stages in the pre-Perth Readvance shoreline displacement which may be referred to as EF-7 to EF-10. The localised occurrence of this evidence does not warrant the calculation of shoreline gradients. The component fragements are as follows:

Table 8-3

Shoreline	North Coast	South Coast
EF-7	---	Fragments F/Y & F/Y_1
EF-8	Fragments H_1 & L_1	Fragments F/Z & F/Z_1
EF-9	Fragments K_1, Q_1 & R_1	---
EF-10	Fragment J_1	---

b) Relation of the raised shorelines to deglaciation

It was noted above that on the north coast (Area A), shoreline fragments higher than the Randerston Shoreline (EF-3) are confined to the eastern part of the area, within 5 km of Fife Ness, and evidence of the Wormistone (EF-2) or any higher shoreline is totally lacking west and northwest of Boghall. Although the rims of kettles descend to 30 m O.D. and below near Boghall and near Pitmilly (Fig. 3.1), they are not conclusively lower than the level given by extrapolation of the Wormistone Shoreline (EF-2), in either the WNW-ESE or W18°N-W18°S planes of projection. Near Boarhills, however, a meltwater bench that is part of a well developed system of subglacial meltwater channels and benches descends to the level of the Randerston Shoreline (EF-3), as described earlier (Chap. 3). The clarity of this feature suggests that since it was formed, sea level has not been higher than the Randerston Shoreline, and it is therefore probable that the reason for the absence of the Wormistone (EF-2) or any higher raised shoreline west of Boghall is the contempraneous presence there of glacier ice.

The shorelines lower and thus younger than the Wormistone Shoreline all extend farther west-northwest towards St. Andrews, where the Kingsbarns Shoreline (EF-4), represented by fragment D_1 (Fig. 3.2), merges with an extensive outwash plain (5, Figs. 8.1 & 8.4) deposited when the ice margin lay just west of St. Andrews (Chap. 3). A younger and lower outwash fan, 7, was also deposited when the ice margin lay close to St. Andrews, but there is no clear connection with a particular raised shoreline. A third outwash terrace, 8, was probably formed when the wasting ice margin lay near Guard Bridge, and since it descends to a slightly lower level than that given by extrapolation of the Kinkell Shoreline (EF-6), it may be slightly younger than the latter, although the possibility of contemporaneity cannot be excluded.

With the exception of plateau 14, all of the fluvioglacial terrace complexes in the Wormit Gap (9-15, Figs. 8.1 & 8.4) descend below the level given by extrapolation of the Kinkell Shoreline (EF-6). However, plateau 11 and plateau-terrace complex 12/13 do not descend far below this level, particularly in the W18°N-E18°S plane (Fig.8.4), in which the lower end of plateau 11 lies at almost the same altitude as that given by extrapolation of Shoreline EF-6. Bearing in mind the errors involved in extrapolation, it is therefore possible that the base level controlling the formation of plateaus 11, 12/13 and 14 was the relative sea level responsible for Shoreline EF-6. However, it is also possible that all of the Wormit Gap outwash features postdate EF-6, for it is not known how much of the lower ends of the plateaus and terraces has been eroded away: like fan 15, they may originally have descended to much lower levels than that given by extrapolation of EF-6. All that may be stated with reasonable certainty is that large masses of decaying glacier-ice remained in the Wormit Gap after the formation of EF-6 and, as was shown earlier (Chap. 3), some detached ice masses remained throughout the succeeding phases of shoreline displacement represented by Shorelines EF-7 to EF-10.

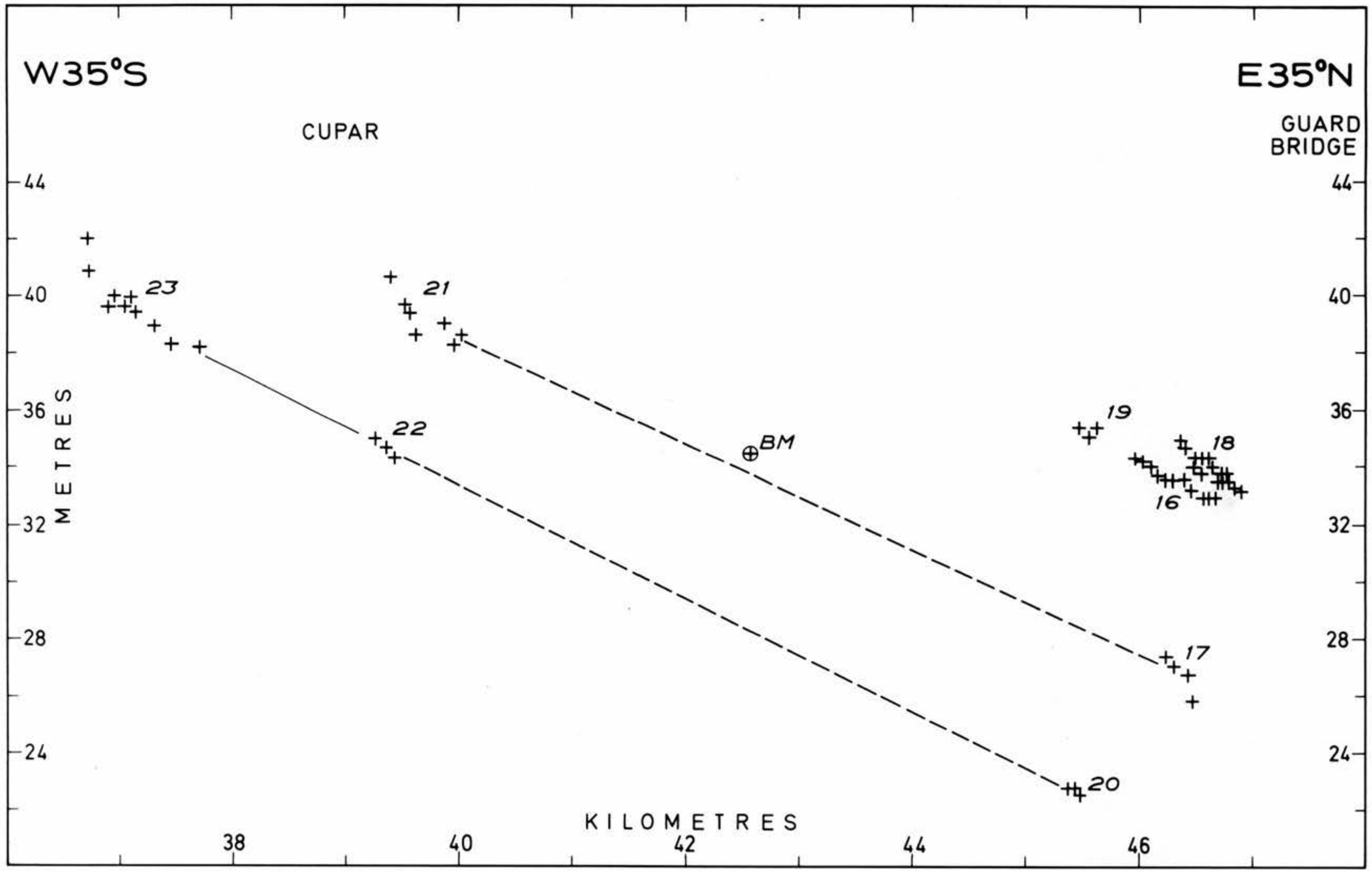


FIGURE 8.5 - Height-distance diagram, Stratheden fluvioglacial terraces: W35^{O}S-E35^{O}N plane.

The fluvioglacial terraces in Stratheden (16-23, Figs. 8.1, 8.4, & 8.5; Chap.3) all postdate terrace 8, and therefore Shoreline EF-6 as well. Together with the associated kames and kettles, they record phases of ice decay in Stratheden that are approximately equivalent to those in the Wormit Gap, although the precise correlation between the two areas is not known.

The relationship of the laminated marine clay of Stratheden and the Eden estuary area to the raised shorelines discussed above remains problematic. As pointed out earlier (Chap.3), if one accepts the likelihood of the clay being one broadly contemporaneous deposit, then it indicates a glacial readvance, for it predates all of the successive outwash terraces and associated former ice-margin positions between St. Andrews and Cupar. There is nothing in the shoreline sequence to suggest an interruption or retardation of isostatic recovery such as might be caused by a glacial readvance (Chap.10), but it is possible that the readvance occurred before any of the East Fife shorelines was formed, the limit being that associated with Shoreline EF-1 or, even earlier, the Aberdeen-Lammermuir Readvance itself. A difficulty that confronts these hypotheses is that, to the writer's knowledge, no till has ever been recorded as intervening between the clay and the overlying fluvioglacial materials, although the same is true in the case of the better-documented Perth Readvance (Chaps. 5 & 10).

On the south coast of eastern Fife, the lateglacial raised beaches are closely associated with the products of ice decay, as described elsewhere (D.E.Smith, 1965; Cullingford & Smith, 1966).

Shoreline 1 (EF-1), which is almost continuous from Fife Ness to north of Anstruther, merges at the latter place into fluvioglacial mounds, and was therefore probably formed in association with an ice-front near Anstruther. There is profuse evidence that, during the formation of Shorelines EF-2 to EF-5, the area fringing the eastern part of Largo Bay was the scene of abundant deposition of fluvioglacial material in, under, over, and between masses of decaying ice, some small remnants of which outlasted the formation of EF-6 and even EF-7. Shorealines EF-7 and EF-8, evidence for which is confined to the western part of Largo Bay, were formed contemporaneously with large pitted outwash plains in the Leven valley.

The evidence of both coasts of eastern Fife together thus points to successively lower and more gently inclined raised shorelines penetrating progressively farther west in association with a westward-receding ice margin. These relationships are partly depicted on maps of isobases and ice-margin positions for Shorelines EF-4 to EF-6 (Fig.8.3), and the implications for the general nature and pattern of shoreline displacement will be considered later (Chap.10).

2. Other pre-Perth Readvance raised shorelines

Evidence of possible raised shorelines formed after the East Fife series and before the Perth Readvance consists of only 5 fragments: B/D, D/R, D/E_1, D/F_1, and D/G_1 (the letter preceding the stroke indicates the area in which the fragment occurs, where this is not otherwise clear). With such scanty information it is not certain that all of these features are in fact raised beach fragments, particularly as 2 of them (D/R & D/E_1) are very small features each measured at only 3 points. Fragment D/G_1, at 31.6-32.1 m, is so much higher than any other shoreline feature in Areas B and D that its marine origin might be questioned on that basis alone: it could, for example, be a structural bench veneered with drift. It is the highest member of a staircase of 4 lateglacial terraces, the lowest of which, D/D_1, is part of the Main Perth Raised Shoreline (sec.3). The other members, D/E_1 and D/F_1, occur in a similar altitudinal belt to that occupied by B/D and D/R (Fig.8.6; the field constraints for Areas B to D are listed in sec.3).

Fragment B/D is morphologically continuous with fluvioglacial terrace B/3, which may relate to a former ice margin near the site of Newburgh (Chap.4). Fragments D/E_1 to G_1, assuming they are all raised beaches, also either predate or are contemporaneous with the occupation by glacier-ice of the Baledgarno-Benvie depression, where one kettle rim is at least as low as 27 m, and where a pitted outwash plain descends to a level below that of E_1 (Chap.6). It therefore seems reasonable to regard these raised shoreline fragments as having been formed in association with the continued westward recession of the ice margin following the formation of the East Fife series of shorelines.

Fluvioglacial fan B/1 was formed at a time when local relative sea level was 22 m or less (Chap.4), but there is no evidence to show whether it is younger or older than the raised shoreline fragments discussed above. The former possibility would require the survival of detached ice masses in the northern part of the Wormit Gap or in the hills of northern Fife after the main ice-margin had receded to the positions stated above; whilst the latter possibility would require a minimal gradient of the shoreline of which fragment B/D is a remnant of about 0.7 m/km in the W18°N-E18°S plane (Fig.8.6), and about 0.6 m/km in the W7°N-E7°S plane (Fig.8.8), and much steeper gradients for the higher shorelines. Minimal gradients of the same order are indicated by the existence of kettles with rims as low as 16.8 m near Leuchars (Chap.3; Figs. 8.1 & 8.4), which implies that at the time sea level was at 26-27 m about 4 km northeast of Newburgh, it did not exceed about 17 m near Leuchars.

Evidence of raised beaches merging with outwash spreads during the same phase of ice recession is clearer and more abundant on the south side of the Forth in and around Edinburgh, although the features are localized, and minimal shoreline gradients have to be inferred in the same way as above (Sissons, Smith & Cullingford, 1966).

3. The Perth Readvance raised shorelines

Apart from the 5 fragments dealt with above (sec.2), the evidence of lateglacial raised beaches and shorelines in the Earn-Tay lowlands, comprising Areas B,C, and D, relates to the Perth Readvance and the ensuing period of deglaciation (Chaps. 1 & 5).

The height data were plotted initially on shoreline diagrams constructed in WNW-ESE and W18°N-E18°S planes of projection. Figure 8.6 is in the latter plane, this having been found appropriate for the earlier East Fife shorelines.

The field constraints for Areas B,C, and D are as follows:

<u>Area B</u> (Tables 4-1 & 4-5)

$$\frac{))D}{(A)\text{-}B\text{-}C}\ ,\ \frac{F}{E}\ ,\ \begin{array}{c}H\\ \hline G\\ \hline E\end{array}\ ,\ \frac{K}{I\text{-}J}\ ,\ \begin{array}{c}L,(O)\\ \hline (N)\\ \hline M\end{array}\ ,\ \frac{P}{C/A}\ ,\ Q\ ,\ \begin{array}{c}S,U\\ \hline (R)\\ \hline T\end{array}\ ,\ \begin{array}{c}X\\ \hline W\\ \hline V\end{array}$$

<u>Area C</u> (Table 5-1)

$$\frac{B/P,C}{A\text{-}B}\ ,\ \begin{array}{c}E\\ \hline G\\ \hline (D)\end{array}\ ,\ F\ ,\ \begin{array}{c}))K\\ \hline (I),J\\ \hline H\end{array}\ ,\ (L)\ ,\ (Y)$$

<u>Area D</u> (Table 6-3)

$$A\ ,\ \begin{array}{c}(B),D\\ \hline C\\ \hline E\end{array}\ ,\ \frac{G}{F\text{-}S\text{-}T}\ ,\ \begin{array}{c}I\\ \hline H\\ \hline J\end{array}\ ,\ \begin{array}{c}N\\ \hline M\\ \hline L,O\end{array}\text{-}P\text{-}\begin{array}{c}(R)\\ \hline Q\\ \hline H,(K)\\ \hline J\end{array}\ ,\ \begin{array}{c}Y\\ \hline V\\ \hline U,W\\ \hline X\end{array}\ ,\ \frac{Y}{Z}\ ,$$

$$A_1\ ,\ B_1\ ,\ C_1\ ,\ \begin{array}{c}G_1\\ \hline F_1\\ \hline E_1\\ \hline D_1\end{array}\ ,\ H_1\ ,\ (I_1)$$

a) <u>The Main Perth Raised Shoreline</u>

By far the most conspicuous lateglacial raised shoreline in the

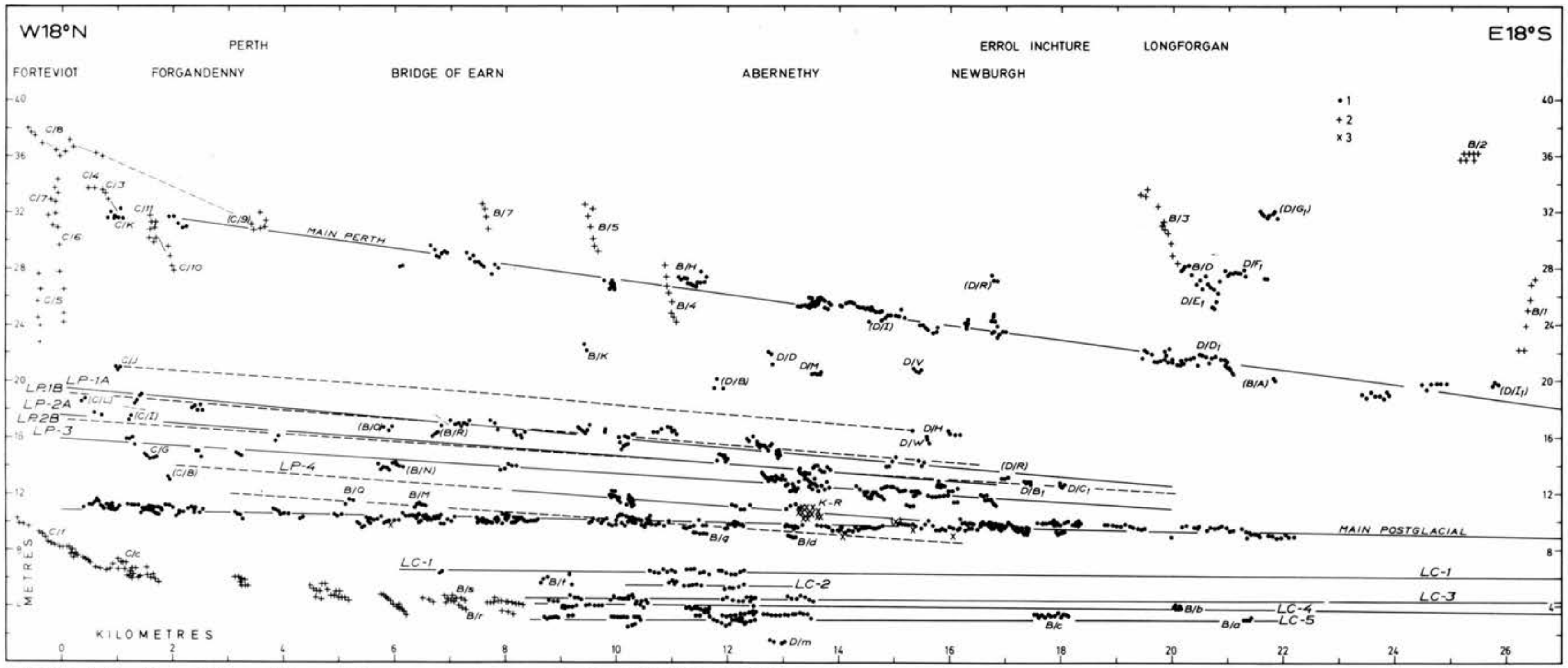


FIGURE 8.6 - Shoreline diagram, Areas B-D: W18°N-E18°S plane. 1. Raised shoreline heights; 2. Fluvioglacial terrace heights; 3. Buried shoreline heights. Details of best-fit lines: Main Perth, N=178, Y=32.7208-0.5444X, r=-0.9898; LP-1A, N=94, Y=19.4886-0.3478X, r=-0.9513; LP-1B, N=84, Y=19.1356-0.3060X, r=-0.9351; LP-2A, N=31, Y=17.5812-0.2885X, r=-0.9052; LP-2B, N=41, Y=17.3065-0.2644X, r=-0.9263; LP-3, N=108, Y=15.9187-0.2508X, r=-0.9390; LP-4, N=40, Y=14.4738-0.2786X, r=-0.8651; Main Postglacial, N=406, Y=10.8184-0.0724X, r=-0.8528; LC-1, N=27, Y=6.7624-0.0319X, r=-0.9299; LC-2, N=14, line estimated; LC-3, N=57, Y=4.7290-0.0189X, r=-0.8689; LC-4, N=42, Y=4.3341-0.0275X, r=-0.5360; LC-5, N=78, not significantly different from horizontal; (N.B. the best-fit lines for LC-1 & LC-3 refer to the whole Earn-Tay-East Fife area).

Earn-Tay lowlands, in terms of both field morphology and representation on shoreline diagrams (Figs. 8.6, 8.8, & 8.9), is the Main Perth Raised Shoreline. It stands out on diagrams covering a wide range of planes of projection as a striking alignment of 178 heights, comprising the following fragments: (A), B,C,F,H,S,U, and X in Area B; E,K, and (Y) in Area C; and (I),N,P,Q,Y,D_1, and H_1 in Area D (the bracketed fragments being excluded from all calculations for reasons stated earlier; Chaps. 4-6). It thus includes some of the longest and most extensive raised beach fragments, and forms the highest recognizable lateglacial marine feature west of Errol and Newburgh (Chaps. 4-6).

The shoreline slopes down from about 32 m near Forteviot, in the Earn valley, to 19-20 m near Invergowrie, west of Dundee, its gradient in the Earn-Tay lowlands being 0.54 m/km in the W18°N-E18°S plane. The linear trend surface for the same data (trend surface B, Fig. 8.7) slopes down towards E13°S at a gradient of 0.51 m/km.

The Main Perth Raised Shoreline is also the most conspicuous lateglacial shoreline in the vicinity of the western part of the Firth of Forth (Sissons & Smith, 1965b), and its gradient in the W18°N-E18°S plane, 0.44 m/km, is similar to that in the Earn-Tay lowlands. Trend surface analysis lends further support to the idea that the Main Perth Raised Shoreline is an approximately synchronous feature in the Earn-Tay and western Forth areas, the surface for the latter sloping down towards E16°S at a gradient of 0.44 m/km (trend surface A, Fig. 8.7). There is therefore a close similarity

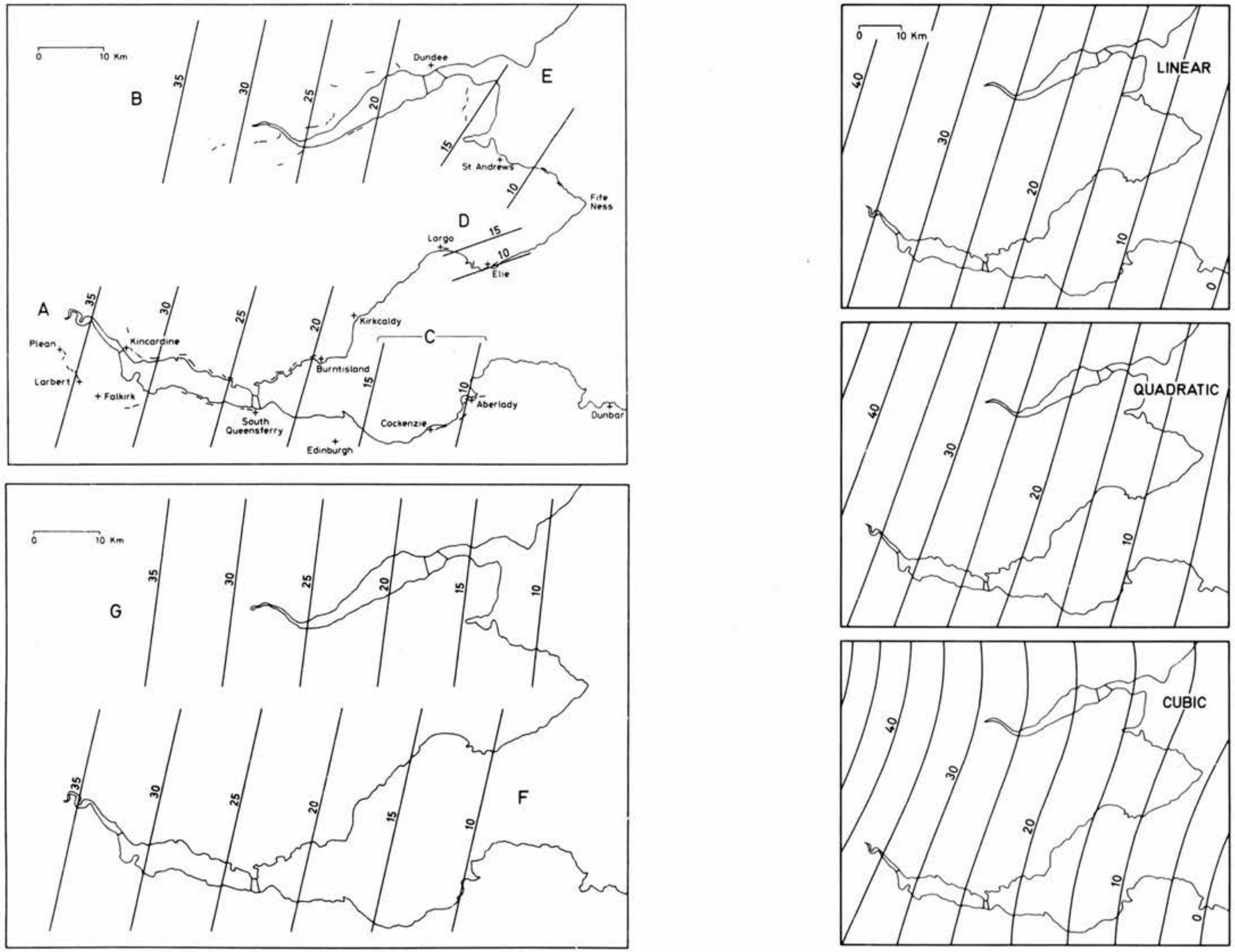


FIGURE 8.7 - Isobases of the Main Perth Raised Shoreline in the Tay-Forth region (after Smith, Sissons, & Cullingford, 1969).

between the isobases for the two areas. As stated elsewhere (Smith, Sissons & Cullingford, 1969), the difference in gradient of the respective linear surfaces of 0.07 m/km cannot be attributed to difficulties in field measurement, because of the clarity of the feature and the large number of measurements in both areas. The difference may reflect different conditions of lateglacial sedimentation in the two estuaries as influenced by such factors as rate of sediment supply, estuarine configuration, and exposure, and together with the small difference (3^{o}) in the direction of slope, it may also partly reflect the respective positions of the two areas in relation to the overall pattern of isostatic deformation (Chap.10).

For considerable distances eastwards from both the Earn-Tay lowlands and the western Forth area, the Main Perth Raised Shoreline is either missing or cannot be measured accurately, so that it is not possible to trace it from the western areas into either East Fife or East Lothian. As pointed out previously (Smith, Sissons & Cullingford, 1969), however, the identification of this shoreline in the eastern areas is facilitated by the existence of upper and lower limits imposed by earlier and later shorelines, an upper limit being imposed, in East Fife at least, by the lowest of the pre-Perth Readvance shorelines identified earlier (sec.1), and a lower limit by the Main Postglacial Raised Shoreline (Chap.9), unless the Main Perth feature is so low as to have been obliterated by the Main Postglacial shoreline. The upper limit for the Main Perth feature is further restricted in these eastern areas by the altitudes of kettle holes, unless one assumes that the melting of the glacier-ice that produced these holes was unduly protracted.

Within this altitudinal zone in both East Fife and East Lothian there occur stretches of lateglacial raised shorelines that, on the basis of their clarity, gradient, and closeness to the levels given by extrapolation of the best-fit lines and surfaces from the western areas, are likely to be part of the Main Perth shoreline.

In northeastern Fife (Area A), a well-marked feature that is likely to be part of the Main Perth shoreline is continuous for 5 km north of Leuchars at an altitude of 15.5-17.0 m, and comprises fragments G_1, I_1, N_1, and O_1. The higher raised beaches that occur inland of this shoreline are pitted by several kettle holes, the lowest kettle-rim altitude being 16.8 m (Chap. 3). The altitude of the well-marked raised shoreline in the immediate vicinity is 15.5-16.4 m. As Chisholm (1966) argues, the occurrence of kettles in the higher raised beaches implies that glacier ice still occupied these holes when the beach deposits accummulated. The kettles have a greater significance, however, for they do not occur below the 15.5-17.0 m shoreline. This sudden disappearance of kettles is difficult to explain if the latter shoreline is interpreted simply as a member of a series of successively lower shorelines formed during the deglaciation of the local area, but if it is interpreted as the Main Perth Raised Shoreline and marks the limit of a much later transgression, the absence of kettles below the shoreline is readily explicable.

Farther along the Fife coast, southeast of St. Andrews, only 2 measurable features that can be attributed to the Main Perth shoreline have been identified: fragments A/L and A/U.

The gradient of the shoreline in Area A is 0.43 m/km in the WNW-ESE plane (Fig.8.1), and 0.44 m/km in the W18°N-E18°S plane (Fig.8.4). In both cases the best-fit line passes through the data obtained on fragment P_1, which were not included in the calculations because of the marginal suitability for measurement of this steeply shelving feature. The linear trend surface for Area A (trend surface E, Fig.8.7) slopes down towards E34°S at a gradient of 0.42 m/km. The direction of slope and the gradient thus differ by 21° and 0.09 m/km respectively from those calculated for the Earn-Tay lowlands (Areas B-D), but this divergence must be viewed in the light of the disadvantage of using trend surface analysis for a single length of coastline: much better control on the form of the computed surface is obtained by using data from at least two opposite coasts, as in the case of the Earn-Tay and western Forth areas. Furthermore, there is greater possibility in a small, more exposed area for local factors affecting beach formation to mask the regional trend. In view of such drawbacks, the linear surface computed for the 74 heights in East Lothian (surface C, Fig.8.7), which slopes down towards E14°S at 0.35 m/km, is in remarkably close agreement with that calculated for the western Forth area, the direction of slope and the gradient differing by 2° and 0.09 m/km respectively. The linear surface

(D, Fig.8.7) computed for the 18 heights attributed to the Main Perth shoreline on the south coast of East Fife (D.E.Smith's Area F), however, is markedly anomalous, even allowing for the above limitations and the small number of heights, the direction of slope and the gradient being E71°S and 1.25 m/km respectively. However, 8 of these heights were obtained on the second lowest of the rock platforms veneered with beach deposits at Kincraig Point, and some of the other 10 altitudes are probably influenced by blown sand.

The linear trend surface computed for all 3 eastern areas (both coasts of East Fife together with East Lothian) slopes down towards E16°S at 0.45 m/km, whilst that calculated for the western areas (the Earn-Tay and western Forth areas) slopes down towards E18°S at 0.46 m/km. The isobases for the eastern areas as drawn by trend-surface analysis are thus consistent with the conclusion reached on morphological grounds that the shorelines referred to, at least in Area A and in East Lothian, are part of the Main Perth Raised Shoreline.

Isobases were also constructed for the Earn-Tay lowlands with Area A (trend surface G, Fig.8.7) and for all of the Forth data (F, Fig.8.7), the former sloping down towards E7°S at 0.43 m/km, and the latter towards E13°S at 0.42 m/km. Finally, isobases for the whole Tay-Forth region were constructed, the linear, quadratic, and cubic trend surfaces being shown in Figure 8.7. The linear surface, of course, masks the slight variations in direction and amount of slope between the Tay and Forth areas, but its direction of slope (E17°S) is very similar to that (E18°S) calculated for the older East Fife shorelines (sec.1), which occur on the promontory separating the two firths. This confirms that a vertical plane aligned W18°N-E18°S is a meaningful one in which to construct shoreline diagrams in the Tay-Forth region, at least for lateglacial shorelines, and as a starting point for subsequent analysis.

The gradients and directions of slope relating to different parts of the Main Perth Raised Shoreline are summarized in the following table:

Table 8-4

Area	N	Best-fit line in W18°N-E18°S plane		Linear trend surface		
		Gradient m/km	r	Direction of slope down	Gradient m/km	%SS
Earn-Tay	178	0.54	-0.990	E13°S	0.51	98.24
W. Forth	208	0.44	-0.990	E16°S	0.44	98.46
E.Fife (Area A)	44	0.44	-0.994	E34°S	0.42	99.06
E.Fife (Area F)	18	0.72	-0.875	E71°S	1.25	91.25
East Lothian	74	0.37	-0.938	E14°S	0.35	93.34
Tay-Forth E. areas	136	0.41	-0.971	E16°S	0.45	95.55
Tay-Forth W. areas	386	0.46	-0.985	E18°S	0.46	97.78
Earn-Tay + Area A	222	0.45	-0.991	E7°S	0.43	98.77
Forth (all data)	300	0.43	-0.997	E13°S	0.42	99.59
Tay-Forth (all data)	522	0.43	-0.995	E17°S	0.43	99.24

b) Lower Perth raised shorelines

There is abundant evidence in the Earn-Tay lowlands (Areas B-D) of lateglacial raised shorelines that are lower and younger than the Main Perth Raised Shoreline, and were formed as the ice wasted back from the readvance limit. The recognition of contemporaneous features is not so straightforward as in the case of the Main Perth shoreline in the same area, however, because successive shorelines are relatively closely spaced altitudinally, and the approximately SW-NE alignment of the Earn-Tay lowlands is somewhat oblique to the general trend of the isobases, making the bearing of the plane of projection used rather critical. This means that relatively small changes in the bearing of the plane of projection can result in relatively large changes in the relative positions of the measurements on shoreline diagrams. This caused little difficulty in the case of the Main Perth shoreline because of the clarity and continuity of this feature over long distances, but the Lower Perth fragments, although sometimes extensive, are in general more fragmented, and diagrams in different planes suggest different correlations. For this reason, 4 planes of projection were used: W18°N-E18°S (Fig.8.6), W7°N-E7°S (Fig.8.8), W13°N-E13°S (Fig.8.9), and W37°N-E37°S (Fig.9.2). These planes were chosen for the following reasons: the first is that found to be most relevant for the pre-Perth Readvance shorelines of East Fife, and is close to the regional diection of slope of the Main Perth Raised Shoreline in the Tay and Forth; the second is the direction in which the Main Perth feature slopes in the

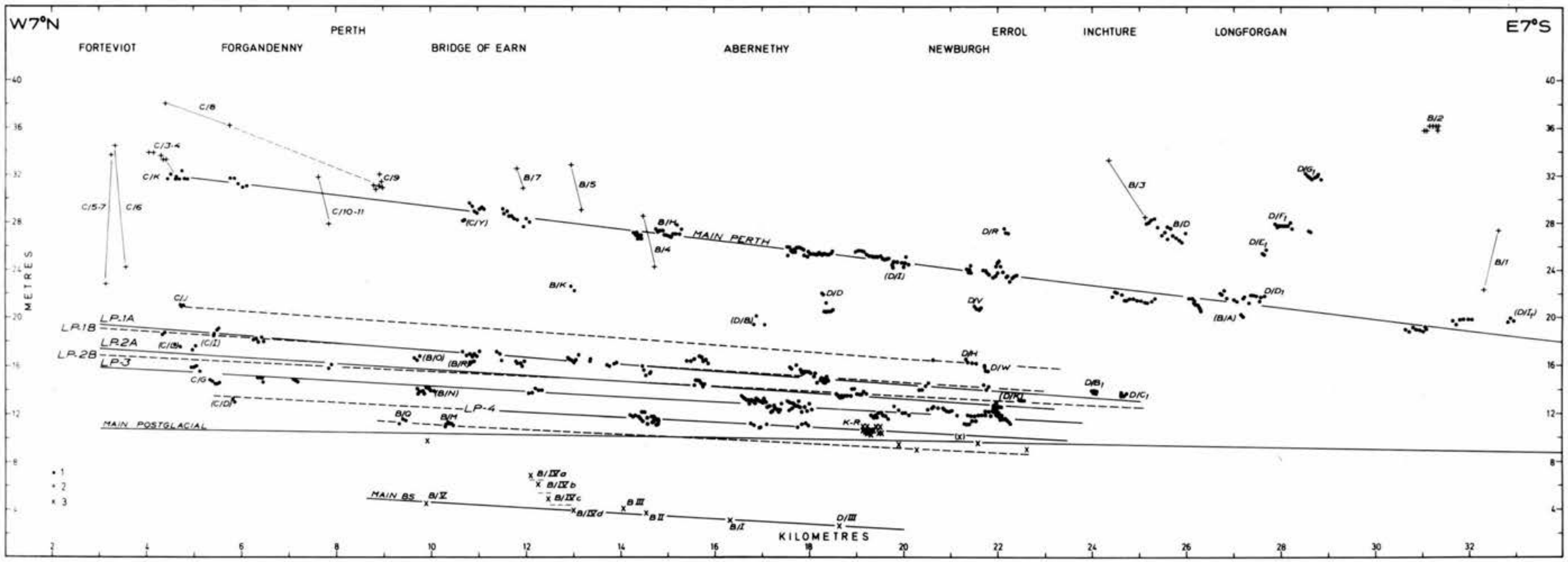


FIGURE 8.8 - Shoreline diagram, Areas B-D: W7°N-E7°S plane. Symbols as in Figure 8.6. Details of best-fit lines: Main Perth, N=178, Y=34.0510-0.4732X, r=-0.9900; LP-1A, N=94, Y=20.2262-0.2889X, r=-0.9575; LP-1B, N=84, Y=19.8474-0.2594X, r=-0.9371; LP-2A, N=31, Y=18.2300-0.2439X, r=-0.9504; LP-2B, N=41, Y=17.7038-0.2114X, r=-0.9498; LP-3, N=108, Y=16.5891-0.2208X, r=-0.9432; LP-4, N=40, Y=14.6781-0.2087X, r=-0.8727; Main Buried Shoreline (Main BS), N=6, Y=7.0504-0.2371X, r=-0.9482; Main Postglacial, N=406, Y=11.0202-0.0631X, r=-0.8238.

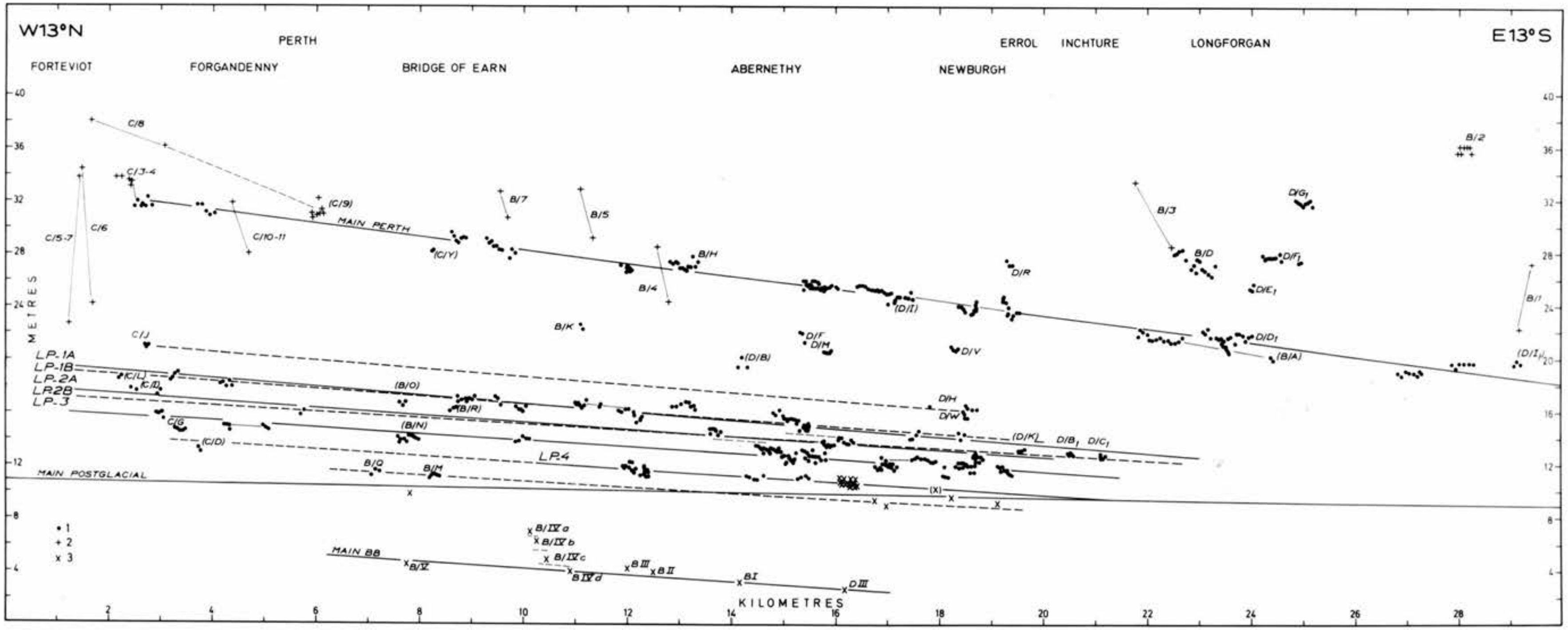


FIGURE 8.9 - Shoreline diagram, Areas B-D: W13^{o}N-E13^{o}S plane. Symbols as in Figure 8.6. Details of best-fit lines: Main Perth, N=178, Y=33.3910-0.5083X, r=-0.9910; LP-1A, N=94, Y=19.8711-0.3179X, r=-0.9558; LP-1B, N=84, Y=19.5032-0.2828X, r=-0.9381; LP-2A, N=31, Y=17.9395-0.2675X, r=-0.9321; LP-2B, N=41, Y=17.5298-0.2375X, r=-0.9409; LP-3, N=108, Y=16.2633-0.2363X, r=-0.9435; LP-4, N=40, Y=14.6025-0.2422X, r=-0.8719; Main Buried Shoreline (Main BB), N=6, Y=6.5997-0.2422X, r=-0.9370; Main Postglacial, N=406, Y=10.9196-0.0677X, r=-0.8397.

Earn-Tay and East Fife area; the third is the local direction of slope of the Main Perth shoreline in the Earn-Tay lowlands; and the last is orthogonal to the trend of the Main Postglacial isobases in the Earn-Tay area (Chap.9). By analogy with the Main Perth data, the W13°N-E13°S plane should be the most appropriate for the Lower Perth data in Areas B-D, but it was thought advisable to allow for changing isobase trends by considering other possibilities.

For the correlation of the Lower Perth fragments, 3 schemes may be postulated that obey the field constraints and produce close alignments on shoreline diagrams. Two of the schemes differ only in respect of 2 fragments. The shorelines of the 3 schemes have constituent fragments as listed in Table 8-5, and the gradients and correlation coefficients of the best-fit lines in all 4 planes of projection are listed in Table 8-6.

Table 8-5

Scheme	Shoreline	Component fragments	N
A	LP-1	B/I, B/J, B/L, B/W, C/C, C/F, D/A, D/C, D/G, D/Z, D/B_1, D/C_1	94
	LP-2	B/G, B/P, D/E, D/X	31
	LP-3	B/E, B/T, C/A, C/B, C/H, D/F, D/J, D/O, D/S, D/T, D/U, D/A_1	108
	LP-4	B/V, D/L, Kilspindie-Rait 'Main Postglacial'	40
B	LP-1	Same as Scheme A, excluding D/B_1 & D/C_1	84
	LP-2	Same as Scheme A, including D/B_1 & D/C_1	41
	LP-3	Same as Scheme A	108
	LP-4	Same as Scheme A	40
C	LP-1	B/I, B/J, B/L, C/C, C/F, D/A, D/W	48
	LP-2	B/G, B/P, B/W, D/C, D/G	46
	LP-3	B/E, B/T, C/A, C/B, C/H, D/E, D/B_1, D/C_1	82
	LP-4	C/G, D/F, D/J, D/O, D/S, D/T, D/X, D/A_1	60
	LP-5	B/V, D/L, D/U	31

Table 8-6

		W7°N-E7°S		W13°N-E13°S		W18°N-E18°S		W37°N-E37°S	
Scheme	Shoreline	m/km	r	m/km	r	m/km	r	m/km	r
A	LP-1	0.29	-0.958	0.32	-0.956	0.35	-0.951	0.50	-0.840
	LP-2	0.24	-0.950	0.27	-0.932	0.29	-0.905	0.27	-0.546
	LP-3	0.22	-0.943	0.24	-0.944	0.25	-0.939	0.30	-0.834
	LP-4	0.21	-0.873	0.24	-0.872	0.28	-0.865	0.34	-0.525
B	LP-1	0.26	-0.937	0.28	-0.938	0.31	-0.935	0.40	-0.831
	LP-2	0.21	-0.950	0.24	-0.941	0.26	-0.926	0.34	-0.641
C	LP-1	0.17	-0.859	0.19	-0.888	0.20	-0.910	0.27	-0.948
	LP-2	0.10	-0.476	0.12	-0.521	0.15	-0.561	0.24	-0.669
	LP-3	0.14	-0.779	0.16	-0.813	0.17	-0.841	0.25	-0.918
	LP-4	0.16	-0.868	0.17	-0.886	0.19	-0.900	0.27	-0.941
	LP-5	0.11	-0.623	0.13	-0.646	0.14	-0.667	0.30	-0.764

Schemes A and B clearly produce close alignments in the W7°N-E7°S, W13°N-E13°S, and W18°N-E18°S planes, and since they differ only in respect of 2 fragments, there is little to choose between them. The best-fit lines of both schemes give poor fits in the W37°N-E37°S plane. Scheme A involves slightly higher gradients than Scheme B for LP-1 and LP-2, and shows a more regular decrease in gradient of successive shorelines, although the comparative paucity of data on LP-2 and LP-4 makes this an insufficient basis for selecting it as the better scheme. Scheme C is markedly inferior to A and B in respect of the alignment of possible shorelines, and is tenable only in the W37°N-E37°S plane. In the other 3 planes, which cover the most likely range of orientations of the orthogonal plane as suggested by the other lateglacial evidence previously discussed, Scheme C produces alignments that are mostly greatly inferior to those produced by the other schemes, and the best-fit lines in general fit the data less closely than is usual with this type of shoreline data. Moreover, even in the W37°N-E37°S plane, 2 of the 5 best-fit lines, including a quarter of the number of fragments, are poor fits for this type of data, and the change in gradient of successive shorelines is somewhat erratic.

It is therefore concluded that the Lower Perth data are best explained by Schemes A and B. The correlation coefficients of the best-fit lines in the different planes (Table 8.6) suggest that the bearing of the most appropriate plane of projection is best approximated by the W7°N-E7°S and W13°N-E13°S planes. This is confirmed by the isobases calculated for Shorelines LP-1 and LP-3, on which the data are most abundant, the directions of slope and the gradients of the linear trend surfaces being as follows:

TABLE 8-7

Shoreline	N	Direction of slope down	Gradient m/km	%SS
LP-1 (Scheme A)	94	E 7°S	0.29	91.76
LP-1 (Scheme B)	84	E12°S	0.28	88.15
LP-3	108	E10°S	0.23	89.23

The lowest major shoreline, LP-4, includes the Kilspindie-Rait 'Main Postglacial' measurements (Table 6-1) which, as explained earlier (Chap 6), were obtained where the carse veneer over the buried raised estuarine materials is so thin that the two deposits are mingled at the surface, so that the measurements may be regarded as applicable to the buried feature. If the best-fit line for LP-4 is extended towards E7°S, E13°S, or E18°S (Figs.8.6, 8.8, & 8.9), it passes close to the altitudes of at least 3 of the buried terrace fragments in the Carse of Gowrie (those located at the SE end of line of bores IV, at the ESE end of line V, and in line VI, Figs.6.2 & 6.4). This suggests that shoreline LP-4 continues eastwards from Kilspindie-Rait as a buried feature.

Below LP-4, a later phase of shoreline displacement is represented by fragments B/M and B/Q, and it is reasonable to assume that this feature too continues eastwards below the carse, perhaps being represented by the other 3 buried terraces located in lines IV, V, and VII (Figs.6.2 & 6.4). A still later stage in the Lower Perth sequence may be represented by the 9.8 m buried terrace located by line V, in lower Strathearn (Figs.4.3 & 4.4). Many more bores will be necessary, however, before sufficient reliable buried shoreline heights are available to allow a reliable correlation of buried shorelines, and of visible with buried shorelines.

Within the altitudinal belt occupied by Shorelines LP-1 to LP-4 there are 8 fragments that have not so far been allocated. 7 of these fragments (B/N, B/O, B/R, C/D, C/I, C/L, & D/K) have been excluded from the calculations for reasons stated previously (Chaps. 4-6), but they all lie close to the best-fit line of one or other of the shorelines postulated. The measurements on fragments B/N and B/O, which were stated earlier to be up to 0.6 m below true shoreline altitudes (Chap.4), accord very well with Shorelines LP-3 and LP-1 respectively if this is taken into account. Fragment B/R lies close to LP-1, C/I and C/L to LP-2, and C/D may be part of LP-4. No reservations were expressed about the measurements of the only fragment still unaccounted for, C/G, which lies between the best-fit lines of LP-3 and LP-4.

In the altitudinal zone between LP-1 and the Main Perth Raised Shoreline there are 8 fragments, of which the lowest 3 (C/J, D/H, & D/W) are about 2-2½ m above LP-1, and probably represent a slightly earlier shoreline. The remaining 5 fragments (B/K, D/B, D/D, D/M, & D/V) are the only ones in a rather wide (7-10 m) altitudinal band between the Main Perth shoreline and the features already discussed. In the Forth area, between Polmont and Stirling, a well-developed raised shoreline occurs about 2-2½ m below the Main Perth feature, and in one locality a third shoreline occurs, about 8-9 m below the Main Perth, but evidence of lower features relating to the immediate post-Perth Readvance period of displacement is lacking (Sissons & Smith, 1965b). It therefore appears that the evidence in the Forth and Tay areas is complementary rather than confirmatory, evidence of the higher post-Main Perth features being largely confined to the Forth, and of the lower features entirely to the Tay.

Finally, the 3 fragments in East Fife (Area A) that occur between the Main Perth and Main Postglacial shorelines (E_1, F_1, & M_1, Figs.8.1 & 8.4) probably belong to the part of the post-Main Perth sequence above LP-1, for in the W7°N-E7°S, W13°N-E13°S, and W18°N-E18°S planes, the best-fit lines of LP-1 and all subsequent features intersect that of the Main Postglacial shoreline near or to the west of where these fragments occur.

c) Relation of the raised shorelines to deglaciation

The Perth Readvance shorelines, including the Main Perth and Lower Perth features, decline less steeply with decreasing age, the gradients of the Main Perth and LP-4 shorelines in the Earn-Tay lowlands being respectively 0.47 and 0.21 m/km in the W7°N-E7°S plane, and 0.51 and 0.24 m/km in the W13°N-E13°S plane.

The Main Perth Raised Shoreline was formed while the ice margin lay at the Perth Readvance limits specified in Chapter 5. This is shown in the Earn valley by the merging of the westernmost Main Perth beach fragment (C/K) with outwash that was deposited when the ice margin lay near the site of Dunning, and in the Tay and Almond valleys by the pitted outwash plain (represented by fragments C/8 & C/9) that declines eastwards from the former ice margin at Almondbank to a level close to that at which the Main Perth shoreline would lie if it were identifiable at that point (as explained in Chap.5, the town of Perth obscures the relationship between the shoreline and outwash features).

In both the Tay and Earn valleys, outwash terraces younger than those formed contemporaneously with the Main Perth shoreline descend well below the level of the latter. In the Tay valley, terrace 10-11 descends 3-4 m below the level given by extrapolation of the Main Perth shoreline; and in Strathearn, terraces 6 and 5/7 descend to altitudes about 8 m and 9 m respectively below that of the Main Perth shoreline in the vicinity, and show no signs of levelling out at those altitudes. Terrace 5/7 continues down almost to the level of the shoreline, represented by fragment C/J, that occurs immediately above Shoreline LP-1 (Figs.8.6, 8.8, & 8.9; the apparent westward slope of 5/7 on the diagrams is spurious, and results from projection into the planes used of an approximately S-N orientated feature). As noted earlier (Chap.5), these outwash terraces were formed when the ice margin still lay near the site of Dunning, so it is evident that a considerable amount of negative shoreline displacement occurred while the wasting ice still lay at or near the readvance limit. This is further emphasized, especially in the Tay valley, by the descent of some proglacial meltwater channels trenching the outwash deposits to the level of the postglacial flats at about 15 m O.D., a level considerably below that given by extrapolation of Shoreline LP-3.

In the Forth area, the evidence concerning the relationship between the Perth Readvance and shoreline displacement is very similar to, but rather more abundant than, that just described (Sissons & Smith, 1965b).

The implications of these relationships for the nature and pattern of shoreline displacement will be considered later (Chap.10).

4. The buried gravel layer

A feature of the Earn-Tay carseland stratigraphy is a layer of sand and gravel overlying the lateglacial marine sediments deposited in association with the Perth Readvance and the ensuing period of deglaciation, and underlying the later buried beach deposits discussed in Chapter 9. This relationship is well shown in lines of bores across lower Strathearn (Chap.4) and across the Tay valley below Perth (Chap.5), and by other, more scattered bores in Areas C and D (Chaps.5 & 6).

A gravel layer in a similar stratigraphic position in the Forth valley has been identified on the basis of many hundreds of borehole records in the Grangemouth-Falkirk-Airth area, where it is 0.3-1.5 m thick, up to 3 km wide, and covers an area of about 28 sq.km (Sissons, Smith, & Cullingford, 1966; Sissons, 1967a, 1969). This layer was formed in intimate association with the planation and cliffing of bedrock, of till, and of the lateglacial marine deposits, which contain many rafted stones and boulders, and it is considered to be largely a lag deposit resulting from a single period of marine erosion of these materials. It slopes fairly uniformly away from its inner margin towards the Forth, at gradients between 1 and 3 m/km, and was probably formed by a transgression that culminated with a fairly prolonged stand of sea level at or slightly above its present level in relation to the land. This must have occurred at some time between the end of the Perth Readvance and the start of deglaciation following the Zone III Readvance, for the High Buried Beach, which is contemporaneous with the culmination of the latter (Chap.9), postdates the gravel layer.

Because of its similar stratigraphic position, it is tempting to postulate a similar origin for the Earn-Tay buried sand-and-gravel layer, but apart from the difficulty of visualizing large-scale marine erosion in the confines of lower Strathearn and the lower Tay valley, and despite the comparative paucity of evidence in these areas, there are certain differences that imply a different origin. First, there is no evidence of planated surfaces of rock, of till, or of marine clay, associated with the gravel layer or any other deposit. On the contrary, the sand and gravel is of extremely variable thickness (0.3-14 m) and rests upon a highly irregular surface that is more suggestive of fluvial or fluvio-glacial channelling of the underlying deposits than of planation (Figs.4.5 & 5.4). Secondly, the surface of the gravel layer in the Friarton-Walnut Grove bores (Fig.5.4) lies at two distinct levels, suggesting terraces at about 5 m and 0-1 m, the surface of the lower one bearing irregularities that may represent former stream channels.

It is therefore likely that the Earn-Tay sand-and-gravel layer, probably including that in the lower Almond valley (Fig.5.4), the surface of which lies at $7\frac{1}{2}$-$12\frac{1}{2}$ m O.D. and is only partly buried, is of fluvial or fluvioglacial origin, and was deposited when local relative sea level was 5 m O.D. or less in the case of the higher terrace, and at or below O.D. in the case of the lower. The period of time available for its formation, which is the same as that stated above for the mid-Forth feature, suggests 4 possibilities: (i) that it is outwash representing a later stage in the post-Perth Readvance deglaciation than that represented by the buried Lower Perth shorelines discussed above (sec.3b); (ii) that it is outwash from glaciers during the cold phase between the Bølling and Allerød interstadials (Chap.1); (iii) that it is fluvial material deposited during one of these interstadials; and (iv) that it is outwash related to the Zone III Readvance, the probable limits of which in the Earn-Tay area (K.S.R. Thompson, personal communication) are shown in Figure 5.5.

With regard to the second of these possibilities, there is as yet no evidence of the limits of such glaciers, and with regard to the calibre of the material, it must be remembered that this may not reliably indicate distance of transport because the sand and gravel was deposited following, and in association with, fluvial or fluvioglacial erosion of the marine clays, which contain many stones and boulders (sec.5a). The gravel content is therefore at least partly derived from pre-existing sediments in the same locality.

Which of the above 4 alternatives is valid remains problematic.

5. General characteristics of the lateglacial raised beaches

a) The sediments

The raised beaches associated with the East Fife pre-Perth Readvance shorelines are composed either of sand, or of sand and gravel, with occasional shell fragments (Chap.3). All available evidence from cliff-top exposures and augering suggests that the depth of the deposits is too great and too variable for them to be explained as veneers of beach deposits over rock platforms, which is how A. Geikie (1902) interpreted them. Only the rock benches on Kincraig Point, on the Forth coast of eastern Fife, are definitely known to be of this nature (D.E. Smith, 1965; Cullingford & Smith, 1966).

The lateglacial marine steps in eastern Fife are therefore essentially of a depositional rather than erosional nature, despite the exposed position of the coast, and in marked contrast to the often erosional character of both the Main Postglacial and present-day shores. This is readily explicable, however, when the probable conditions at the time of their formation are considered. First, there is ample evidence that glacial meltwaters were conveying huge volumes of sediment to the sea at this time, far more than is supplied by the rivers of the present day. Secondly, it is likely that wave attack was less severe than now since the North Sea was probably frozen for a considerable part of the year. Thirdly, the rapidity of the uplift (Chap.10) implies that the waves did not operate at the same level for very long.

In the sheltered Earn-Tay estuarine area the composition of the lateglacial raised beaches is more variable, and is partly related to distance from the former ice margin. This is well shown by the Main Perth Raised Beach, which is composed of coarse sand and gravel where it merges with outwash near Forteviot, sand and finer gravel lower down Strathearn, and fine sand, silt, and clay containing scattered stones and boulders in the Carse of Gowrie. This gradation is locally interrupted where incoming streams contributed coarser materials, as in the case of fragment B/H, near the debouchure of Glen Farg. The surface materials of the Lower Perth beaches are in general finer than those of the Main Perth.

Both the lateglacial estuarine materials of the Carse of Gowrie (Chap.6) and the much older Stratheden clay (Chap.3) contain arctic faunas, and both are laminated and contain scattered stones and boulders, many of which are erratics and are striated. It is very difficult to account for these coarse materials scattered amongst laminated sands, silts, and clays other than in terms of ice-rafting, as has been recognized by almost all workers from Jamieson (1865) to Sissons (1967a). The accumulation of glacio-estuarine sediments and the process of ice-rafting, both by icebergs and by detached fragments of the ice-foot, were observed in Greenland and eloquently described by R. Brown (1870).

The Earn-Tay and Stratheden laminated clays were formerly assigned to the period of the so-called '100-ft beach' (J. Geikie, 1881a-c, 1894; A. Geikie, 1902; Davidson, 1932; Eyles & Anderson, 1946), but this implied contemporaneity is refuted by the evidence that, whereas the Stratheden clay is overlain by fluvioglacial material deposited during the period of deglaciation following the Aberdeen-Lammermuir Readvance, the clays in Strathearn and in the Tay and Almond valleys are overlain only by outwash associated with the later Perth Readvance, while those in the Carse of Gowrie have neither been overridden by ice nor overlain by fluvioglacial material, and at least partly post-date the culmination of the readvance.

The clays in the Carse of Gowrie lie at different levels, the Gallowflat pit, for example, being located on fragment D/M at about $20\frac{1}{2}$ m, and the Inchcoonans pits on fragments D/H and D/J, at 11-16 m (Chap.6). The clays cannot be related simply to different raised beaches, however, for the following reason. It is reasonable to assume that when the laminated deposits that lie beneath the Perth Readvance outwash were being deposited in the Earn and Tay valleys, similar materials were also being deposited in the Carse of Gowrie. At the culmination of the readvance the Main Perth Raised Shoreline was formed, and the associated deposits included not only littoral mudflat and sandflat materials, but also deeper water sediments laid down over the earlier deposits. This relationship was repeated at each succeeding stage in the negative shoreline displacement, although in the later stages it is clear from the morphological evidence that littoral flats became so extensive as to exclude deeper water sedimentation in the Carse of Gowrie. It is thus clear that only the surface layers of material beneath a lateglacial flat relate directly to the raised estuarine flat and shoreline, and it is usual to find that the upper layers are more sandy than the material beneath, which is consistent with deposition in shallower water.

It follows from the above that at any point on the lateglacial flats in the Carse of Gowrie, particularly on the lower flats, a considerable period of deposition is represented in the underlying estuarine materials, which probably include deposits predating, contemporaneous with, and postdating the culmination of the Perth Readvance. Any dating of shells that may in future be carried out must be seen in this light, for unless it is carried out in conjunction with work on the sediments themselves, preferably including varve studies, that may help to relate the dated horizon to a specific part of the chronology of the readvance, the date will only be referable to a rather broad period of events.

b) Relation to alluvial fans

Alluvial fan complexes are numerous in the Earn-Tay area (Chaps. 4-5), and include fan remnants of several ages, from high-level features predating the lateglacial raised beaches to low-level ones that would still be active but for artificial canalization of the streams. Contemporaneity of fan deposition with the Lower Perth shoreline sequence is suggested by parts of the Farg fan complex (Chap.4), and fan deposition related to a base-level lower than that represented by the Main Perth Raised Shoreline, but predating the latter, is suggested by a former gravel pit above the main Craig Burn fan (*3, Fig.6.2), which showed slightly contorted fan material descending beneath laminated clay at about 24-25 m O.D.

c) Dissection

A universal characteristic of the surface form of the lateglacial raised beaches and fluvioglacial terraces is their dissection by numerous gullies and valleys of varying size. This is true not only of the Tay-Forth region (Sissons, Cullingford, & Smith, 1965), but also of other areas, including the Cromarty Firth area (J.S. Smith, 1963).

Evidence that these gullies and valleys are of different ages includes the following:

(i) In some areas there are marked differences in the degree of dissection between raised beaches of different ages, and while in some cases this may reflect different susceptibility to erosion of different materials, in most cases it is a function of time, older and higher features generally being more dissected than lower and younger.

(ii) Some terraces are dissected both by deep gullies and valleys that descend low enough to have been infilled by later estuarine sediments, and by shallow ones that indent the front of the terrace and terminate at their downstream end of the apex of a fan that rests on the later terrace. These two types of feature are clearly of different ages.

(iii) The lower ends of some gullies and valleys are infilled by carse deposits and by sub-carse peat, the base of the latter in a gully near Leuchars having been dated as 9,945$\pm$160 B.P. (Chaps. 3 & 6). There is also evidence north of Leuchars that gully excavation was proceeding during carse deposition, for the carse deposits near the lower end of a gully near Vicarsford (Fig. 3.3) contain sandy material of similar colour and calibre to that of which the gullied lateglacial beach is composed.

It is therefore evident that dissection has continued throughout lateglacial and well into postglacial times. Some gullies may have originated contemporaneously with the beaches into which they are cut, as tidal creeks or channels on the sandflats or mudflats, and some minor gullying almost certainly still occurs on the steeper

frontal bluffs of some terraces. However, the large number of gullies and valley systems that descend below the main carse level implies one or more periods of particularly intense dissection postdating the lowest visible Lower Perth raised beaches and predating the sub-carse peat (Sissons, Cullingford, & Smith, 1965), and evidence in the mid-Forth area shows that at least some of the valleys are infilled by Main Buried Beach deposits, and were therefore largely or entirely formed in lateglacial times (Sissons, 1969).
With regard to the cause of the valleys, it is possible that they were initiated in lateglacial times when relative sea level was high and groundwater consequently higher than now, and that excavation continued in response to a falling water-table controlled by the relative fall of sea level. Alternatively, they may have been cut under periglacial conditions when the ground was frozen and precipitation could not be absorbed. The latter origin has been postulated for features similar to those described above, that dissect raised beaches in Sweden (L.von Post, 1956) and outwash terraces in southern Germany (Büdel, 1944), and are known as 'solifluction ravines'.

Another type of dissection of lateglacial raised beach surfaces is the presence of kettles. Pitted beaches are common in parts of Antarctica (R.L. Nichols, 1961), but the only examples in the Earn-Tay-East Fife area are near Leuchars (Chap.3) and near Bridge of Earn (Chap.4).

CHAPTER NINE

POSTGLACIAL RAISED SHORELINES AND RELATED FEATURES

Introduction

Although postglacial estuarine deposits are much more extensive at the surface than those laid down in lateglacial times, they mostly relate to one raised shoreline - the Main Postglacial Raised Shoreline - and evidence of younger shorelines is confined to the lower Earn and Tay valleys, and a few scattered remnants elsewhere. Little work has so far been carried out on the early part of the postglacial sequence, which lies buried beneath the carse deposits, but the evidence available suggests that several well-preserved flats occur. It is with these latter features that the following account begins.

1. Buried raised shorelines and beaches

In the previous chapter, reference was made to parts of the Lower Perth shoreline sequence that now lie buried beneath carse deposits, and occasionally beneath patchy sub-carse peat. The buried features considered here lie at lower altitudes than the Lower Perth ones, and they generally lie beneath thicker and much more continuous accumulations of sub-carse peat. The evidence so far available, which suggests the presence of 4 flats at different levels, is confined to the lower Earn carselands (Chap.4) and to one line of bores in the southwestern part of the Carse of Gowrie (Chap.6). The approximate altitudes of the buried shorelines in each line of bores are listed, with grid references, in Table 9-1.

TABLE 9-1

BURIED SHORELINE ALTITUDES

Area B	Line I	3.0 m	NO 1862 1771	Area B	Line IVc	4.9 m	NO 1466 1708
"	Line II	3.8 m	NO 1670 1678	"	Line IVd	3.9 m	NO 1529 1776
"	Line III	4.1 m	NO 1623 1688	"	Line V	4.5 m	NO 1228 1874
"	Line IVa	6.9 m	NO 1423 1661	"	M.90	5.0-5.3 m	NO 1372 1763
"	Line IVb	6.2 m	NO 1440 1679	Area D	Line III	2.5 m	NO 2128 2028

These heights are plotted on the W7°N-E7°S and W13°N-E13°S shoreline diagrams (Figs.8.8 & 8.9). from which all other postglacial shoreline heights are omitted, but for reasons of clarity they are not included on the W18°N-E18°S and W37°N-E37°S diagrams (Figs.8.6 & 9.2). They are plotted in these planes on separate diagrams (Fig.9.1), on which the best-fit line for the Main Postglacial shoreline is also shown for comparison.

In the W7°N-E7°S, W13°N-E13°S, and W18°N-E18°S planes, heights B/I, B/IVd, B/V, and D/III fall very closely into a line that slopes down eastwards at gradients of 0.24, 0.25, and 0.26 m/km respectively. B/II and B/III lie close to, but slightly above, this line, and it is not known whether they are parts of the same shoreline, or of the next higher feature as represented by the B/IVc and M.90 heights. If the former case is true, and B/II and B/III are included in the calculation of gradient, the values in the same 3 planes are 0.24, 0.24 and 0.25 m/km respectively. In the W37°N-E37°S plane, the

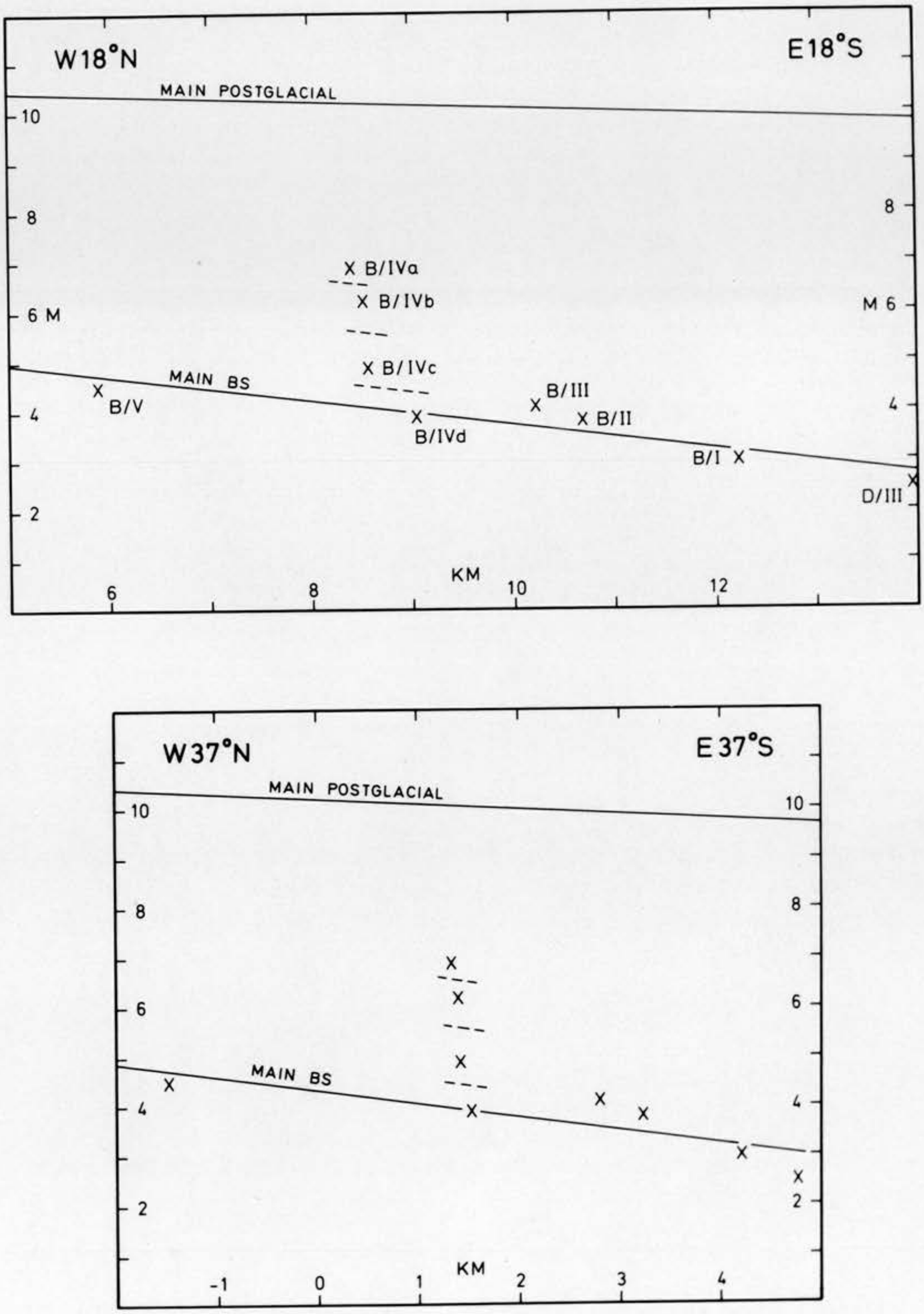


FIGURE 9.1 - Shoreline diagrams: buried raised shoreline heights not plotted on Figures 8.6 & 9.2. Details of best-fit lines for Main Buried Shoreline (N=6): W18°N-E18°S, Y=6.1957-0.2478X, r=-0.9253; W37°N-E37°S, Y=4.3329-0.2788X, r=-0.8487.

alignment is not so close, and the gradient of a best-fit line through the 4 most closely aligned points is 0.32 m/km, and with all 6 points (i.e. including B/II & B/III), 0.28 m/km, although in this plane it seems more reasonable to regard B/II and B/III as parts of the next higher feature.

The above gradient values for the lowest postglacial buried raised shoreline support the conclusion reached earlier (Chap.4), on grounds of morphology and composition, that the buried terraces are of estuarine rather than fluvial origin.

As noted earlier (Chap.4), the extreme base of the sub-carse peat at Carey, resting at 3.1 m O.D. on what is almost certainly the same buried terrace as that represented by B/I and B/IVd, was radiocarbon dated as 9,640$\pm$140 year B.P., suggesting that peat growth started on the emerging surface of the buried beach at about this time. This date is the same as that postulated on the basis of pollen analysis for the transition from estuarine to terrestrial conditions on the surface of the Main Buried Beach in the western Forth area (Sissons, 1966; Newey, 1966). It is therefore tempting to correlate the lowest of the Earn-Tay features with the Main Buried Shoreline, despite the lower average gradient of the latter (bearing in mind that in the Forth area the feature is complicated by dislocation; Sissons, 1972).

The Main Buried Beach of the Forth area is the middle member of a staircase of 3, the High Buried Beach being contemporaneous with the Zone III Readvance moraine at Lake of Menteith, and the Low Buried Beach having been abandoned by the sea about 8,800 radiocarbon years ago (Sissons, 1966). The correlative of the Main Buried Beach in lower Strathearn is the lowest of a staircase of 4 terraces, but the apparent discrepancy between the Forth and Strathearn sequences must be seen in the light of the following considerations.

(i) The data on the Earn-Tay features are incomplete, so the possibility that there is a fifth, lower terrace cannot be discounted.

(ii) The presence of a larger number of buried beaches in the Earn-Tay area is consistent with the larger number of both Lower Perth (Chap.8) and Lower Carse (sec.3) features as compared with the westernForth area.

(iii) The absence of a buried estuarine flat lower than the equivalent of the Main Buried Beach could be readily explained by the estuary having been virtually filled in with sediment during the formation of the Main Buried Beach correlative (cf. the Main Postglacial and subsequent beaches, secs.2-4).

Prior to the onset of carse deposition, the relative sea level fell below that represented by the lowest known buried beach, for the latter is covered by buried peat (Chap.4).

It is not known which of the higher 3 buried beaches near Bridge of Earn correlates with the High Buried Beach of the Forth area.

To summarize, the evidence so far available in lower Strathearn and in the southwestern part of the Carse of Gowrie suggests the presence of 4 buried raised beaches, the lowest of which began to be colonized by terrestrial marsh vegetation about 9,600 years ago, and is therefore probably contemporaneous with the Main Buried

Beach of the western Forth area. It is reasonable to assume that one of the 3 higher features in Strathearn correlates with the High Buried Beach, which was formed while the ice extended to the Zone III Readvance limit, the probable positions of which, in the Earn-Tay area, are shown on Figure 5.5. This means that the early part of the buried beach sequence described here may be strictly speaking of lateglacial age and, together with the character of the deposits (Chaps.4-6; sec.4a), "suggests the possibility that the character of these beaches is related to the wasting away of this ice mass or perhaps to a later minor readvance in the mountains" (Sissons, 1966, p.27).

2. <u>The Main Postglacial Raised Shoreline</u>

a) <u>The Earn-Tay area and eastern Fife</u>

By far the most extensive and continuous raised estuarine flat in the area is that related to the Main Postglacial Raised Shoreline, which has been heighted at 606 points (Tables 3-1, 3-5, 4-2, 4-3, 5-3, & 6-1), of which 42 in Areas A and B have been excluded from the height analysis either because they are located in narrow inlets up which the carse surface rises markedly, or because of anomalously low values attributable to local causes (Chaps.3 & 4). Of the remaining 564 heights, 27 are non-carse heights measured on sandy and shelly beach fragments in East Fife (Chap.3), and 72 were measured in the broad embayments at the northern edge of the Carse of Gowrie, in which the altitude of the carse surface may well have been affected by the influx of alluvial material, adding to the usual tendency for the shoreline to rise up inlets (Chap.6).

The shoreline data in eastern Fife are plotted on diagrams in the WNW-ESE, W18°N-E18°S, and W37°N-E37°S planes (Figs.8.1, 8.4 & 9.2 respectively), and in the Earn-Tay area, on diagrams in the W18°N-E18°S and W37°N-E37°S planes (Figs.8.6 & 9.2 respectively). The gradients and closeness of fit of the best-fit lines in the latter 2 planes are summarized in Table 9-2 (fuller statistical details are given in the captions to the figures). The best-fit line for the East Fife data has a somewhat steeper gradient than that for the Earn-Tay data in the W18°N-E18°S plane, but not in the other plane.

TABLE 9-2

MAIN POSTGLACIAL RAISED SHORELINE - EARN-TAY AREA & EAST FIFE

Data	N	Best-fit line in W18°N-E18°S plane		Best-fit line in W37°N-E37°S plane	
		Gradient m/km	r	Gradient m/km	r
E. Fife (Area D)	86	0.10	-0.936	0.09	-0.944
Earn-Tay (Areas B-D)*	406	0.07	-0.853	0.10	-0.886
Earn-Tay & E. Fife*	492	0.07	-0.954	0.09	-0.964

* Excluding embayment heights

That the embayment heights are anomalously high in relation to the rest of the shoreline is confirmed by the linear trend surface computed for all 564 heights: the residual values of the embayment heights range between -0.15 and +0.91 m, with a mean of +0.33 m, and the surface slopes down towards E45°S at a gradient of 0.10 m/km.

To face Fig. 9.2

FIGURE 9.2

Details of best-fit lines

Main Perth	N=222	Y=27.4219-0.5294X	r=-0.9671
LP-1C	N= 48	Y=17.0225-0.2736X	r=-0.9481
LP-2C	N= 46	Y=15.7015-0.2354X	r=-0.6690
LP-3C	N= 82	Y=14.1475-0.2511X	r=-0.9183
LP-4C	N= 60	Y=13.2723-0.2698X	r=-0.9409
LP-5C	N= 31	Y=12.1469-0.2971X	r=-0.7644
Main Postglacial	N=492	Y=10.1786-0.0858X	r=-0.9637
LC-1	N= 27	Y= 6.4911-0.0365X	r=-0.9277
LC-2	N= 14	line estimated	
LC-3	N= 57	Y= 4.5762-0.0220X	r=-0.8704
LC-4	N= 42	Y= 4.1268-0.0386X	r=-0.6387
LC-5	N= 78	not significantly different from horizontal	

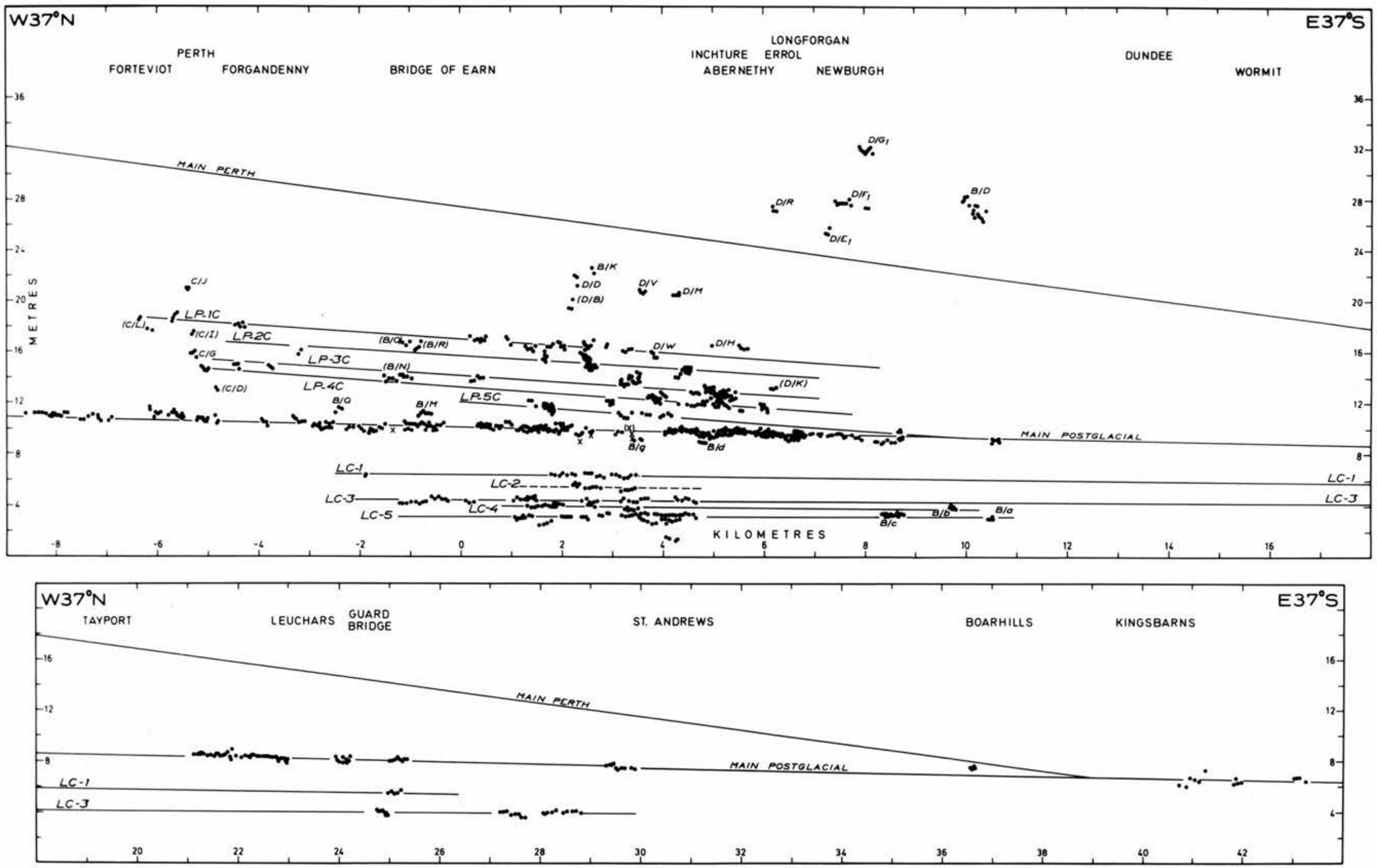


FIGURE 9.2 - Shoreline diagram, Areas A-D: W37°N-E37°S plane. Details of best-fit lines opposite.

If the embayment heights are excluded, the direction of slope and the gradient are E37°S and 0.09 m/km respectively. The isobases as suggested by linear and quadratic trend surfaces computed for all data excluding embayment heights are shown on Figure 9.3.

The direction of slope of the Main Postglacial Raised Shoreline is thus markedly different from that of the Main Perth shoreline (Chap.8), and in order to test the possibility of areas of anomaly, perhaps related to differences in sediment supply, causing the different isobase trend, best-fit surfaces were computed for several different sections of data. The directions of slope and the gradients of the linear surfaces are listed in Table 9-3. This analysis showed that only the inclusion or exclusion of the embayment heights

TABLE 9-3

MAIN POSTGLACIAL RAISED SHORELINE - EARN-TAY AREA & EAST FIFE

Data	N	Linear trend surface		
		Direction of slope down	Gradient m/km	%SS
1. All data	564	E45°S	0.10	90.59
2. Excluding non-carse	537	E46°S	0.10	84.80
3. Excluding embayments	492	E37°S	0.09	93.30
4. Excluding embayments and non-carse	465	E37°S	0.09	89.16
5. Excluding embayments and upper Earn & Tay	381	E37°S	0.08	93.69
6. Excluding embayments, non-carse, and upper Earn & Tay	354	E36°S	0.08	88.41
7. Excluding Area D	299	E38°S	0.09	95.48
8. Excluding non-carse & Area D	272	E37°S	0.09	92.78

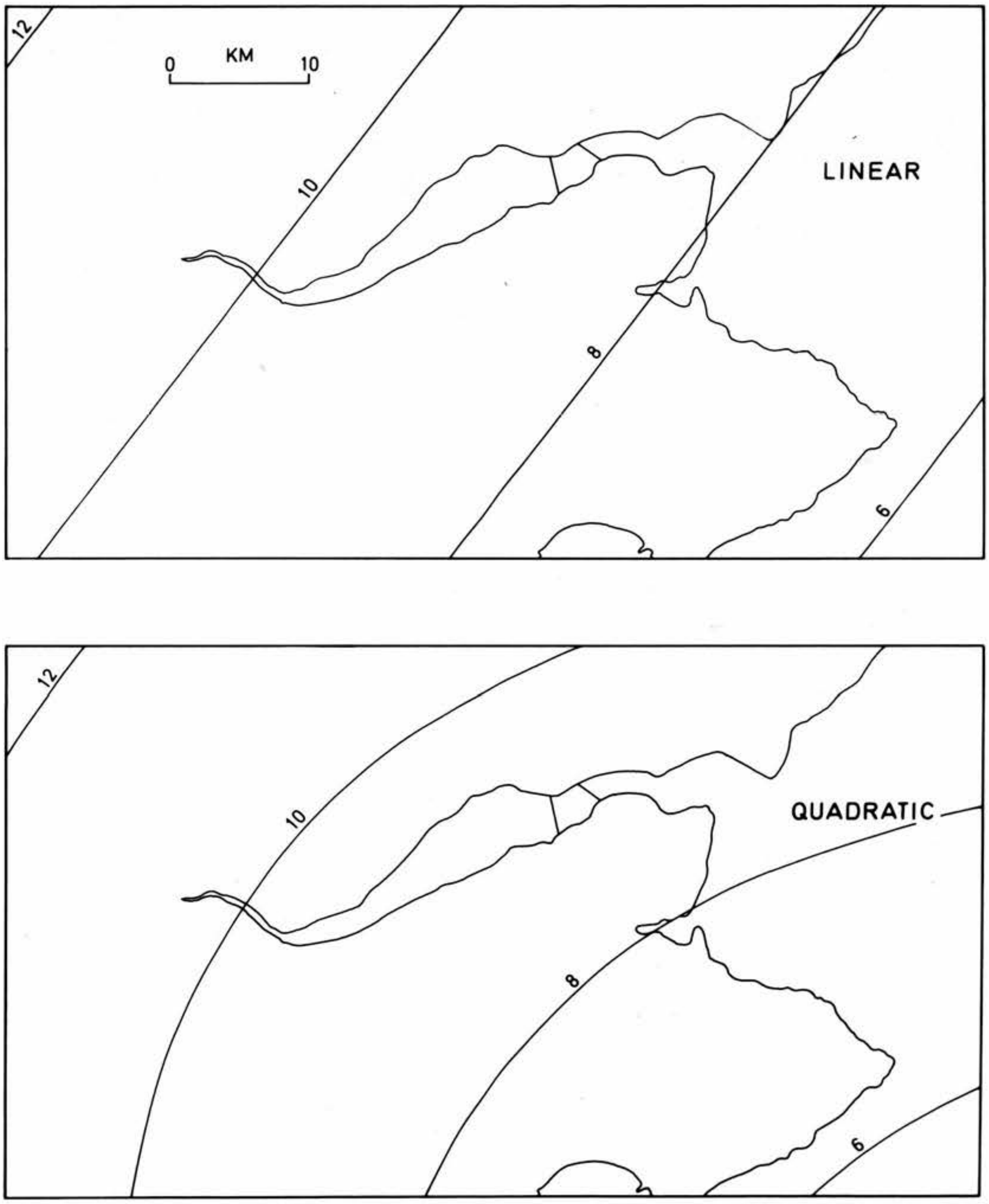


FIGURE 9.3 - Isobases of the Main Postglacial Raised Shoreline in the Earn-Tay-East Fife area (excluding carse embayment heights).

appreciably alter the trend of the isobases, and neither the presence nor the absence of the non-carse heights, or of the upper Earn and Tay valley data (upvalley from Bridge of Earn & Balhelpburn respectively) makes much difference. The exclusion of the latter heights lowers the gradient slightly, to 0.08 m/km, suggesting a slight curvilinearity of the shore plane (Chaps.7 & 10) that is confirmed by the quadratic surface (Fig.9.3). An early impression gained by the writer was that the Carse of Gowrie (Area D) heights are somewhat high in comparison with the rest of the data, but this is not confirmed by the trend-surface data, which show little change if the Area D heights are excluded.

It is thus clear that if the embayment heights are excluded, the Main Postglacial shoreline data show a very consistent pattern of height variation throughout the whole Tay area, the direction of slope being down towards E37°S. The isobase trend thus differs by 24° from that of the Main Perth isobases in the Earn-Tay area, and by 30° from that of the Main Perth isobases in the Tay area as a whole (i.e. including East Fife). This marked difference has important implications for the nature and pattern of shoreline displacement (Chap.10).

b) <u>The Tay-Forth region</u>

The Main Postglacial Raised Shoreline in the western Forth area has a very similar gradient to that in the Tay area: 0.08 m/km in a W-E plane south of the Forth (Sissons, 1963a, 1967a), and the same gradient in a WNW-ESE plane north of the river (D.E. Smith, 1968). The identification of the shoreline is not everywhere as unequivocal in the Forth area as in the Tay, because the carselands lie at 4 fairly extensive levels, the highest of which is somewhat fragmented on the north side of the Forth west of Kincardine, and is almost absent farther east (Smith, 1965, 1968). A further complication is that, although the main carse south of the Forth is very extensive between the head of the carselands and Airth, the shoreline altitude does not decline eastwards uniformly, but in a series of steps (Sissons, 1972). Nevertheless, isobases computed for all the Forth data (including East Lothian) confirm an overall gradient of 0.08 m/km, although they differ markedly from the Tay isobases in having a similar trend to the Main Perth isobases (Chap.8), the linear surface for all the Forth Main Postglacial data sloping down towards E13°S at a gradient of 0.08 m/km, and that for the carse data only sloping down towards E6°S at the same gradient.

Main Postglacial isobases for the Tay-Forth region (excluding Tay embayment heights), as represented by linear, quadratic, and cubic trend surfaces, are shown in Figure 9.4. The linear surface slopes down towards E7°S at a gradient of 0.08 m/km, but this generalization completely masks the marked difference between the Tay and Forth areas just discussed. The higher order surfaces show clearly how the isobases swing sharply eastwards in the Tay area as compared with the Forth, in contrast with the Main Perth isobases, which swing slightly northwards in the Tay area (Fig.8.7).

c) Age

The onset of carse deposition at St.Michael's Wood, near Leuchars, and at Carey, in lower Strathearn, has been approximately dated by radiocarbon dates, for the top of the sub-carse peat, of 7,605$\pm$130 and 7,605$\pm$180 B.P. respectively (Chaps.3 & 4). The altitude of the dated

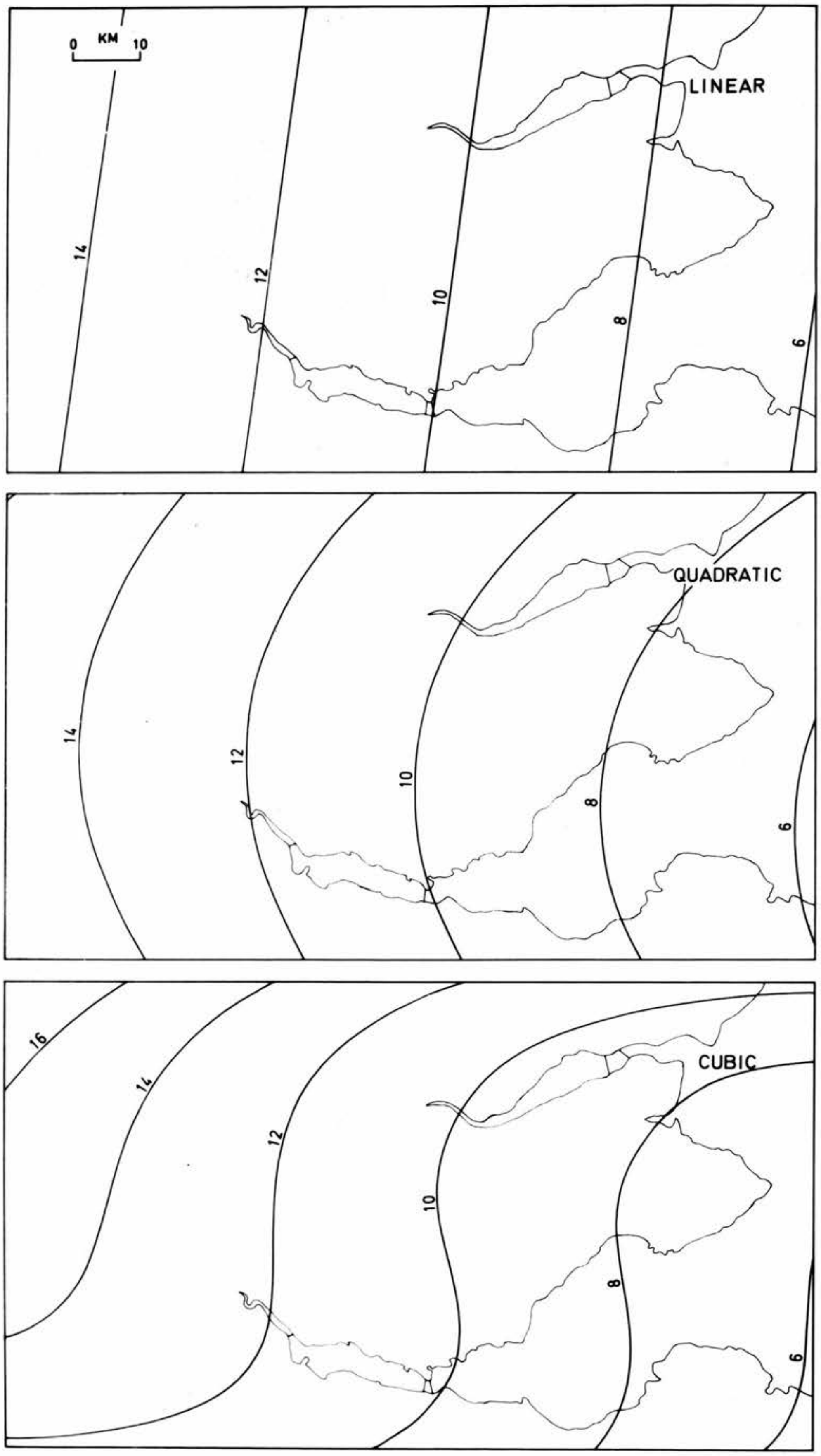


FIGURE 9.4 - Isobases of the Main Postglacial Raised Shoreline in the Tay-Forth region.

sample at Carey is 3.7 m, but the peat has been greatly compressed, and its surface when first submerged must have stood rather higher in relation to O.D. The altitude of the St.Michael's sample, about 6 m, is probably closer to the original altitude of the peat surface there, for the thickness of overlying materials is only about 2½ m, compared with 5.7 m at Carey.

The apparent discrepancy between these dates and that of 8,270±160 B.P. for the top of the sub-carse peat at an altitude of 7.7 m near Kippen, in the Carse of Stirling (Sissons, 1966), is at least partly explained by the locations of the sites in relation to the pattern of displacement. The Main Postglacial Raised Shoreline is 1-1¾ thousand years younger than the dates of inundation of the 3 sites (see below), and near Carey and Leuchars it is respectively about 4 m and 5 m lower than near Kippen. Since older shorelines generally have steeper gradients than younger ones, the height differences between the 3 sites of earlier stages of the Main Postglacial transgression are probably greater than 4 m and 5 m. The height differences of the dated samples are respectively 4.0 m and about 1.7 m, and the Carey peat, being slightly thicker and beneath a similar depth of carse deposits compared with that near Kippen, has probably been compacted as much, although the peat near Leuchars has probably been compacted less. At the time the peat surface near Kippen was inundated, the Carey and Leuchars sites were therefore probably still above the rising estuarine waters, thus at least partly explaining their younger dates of inundation.

Four attempts have been made in the Tay-Forth region to date the maximum of the transgression, and therefore the shoreline. The date of 5,492±130 B.P. (Godwin & Willis, 1962) for wood from the surface peat mantling the western Forth main carse deposits is probably considerably younger than the shoreline, as the sample came from 10 cm above the clay-peat junction. Two unpublished dates from the western Forth carselands place the maximum of the transgression between 6,500 and 7,500 B.P. (Sissons, personal communication). The base of surface peat overlying a wedge of carse deposits near Leuchars was dated as 5,830±110 B.P. (Chap. 3), suggesting that the shoreline may be rather younger in East Fife than in the western Forth area. This is consistent with the higher rate of isostatic recovery in the latter area compared with the former (Chaps. 7 & 10).

3. Later postglacial raised shorelines and river terraces

Apart from 3 fragments in the Eden estuary (A/a, A/b, & A/c, Fig. 3.2, Table 3-1) and 3 between Flisk Point and Newburgh, (B/a, B/b, & B/c, Fig. 4.2, Table 4-2), evidence of raised shorelines formed after the Main Postglacial shoreline is confined to the lower reaches of the Earn and Tay valleys (Chaps. 4 & 5). The field constraints are as follows:

Area A (Tables 3-1 & 3-6)

$$a,\ \frac{c,\ d^*}{b}$$

Area B (Tables 4-2 & 4-4)

$$a,\ b,\ c,\ d,\ e,\ \frac{g}{f},\ \frac{\overset{j}{i}}{h},\ \frac{k,n^*}{l,m^*},\ o^*,\ \frac{p^*}{(p_1^*)},\ \frac{q^*}{(q_1^*)},\ \frac{s}{r^*},\ \frac{\frac{\overset{(t)}{u}}{v}}{w},\ \frac{y}{x},\ (z)$$

Area C (Table 5-4)

$$\frac{a^*}{a_1^*},\ b^*,\ \frac{c^*}{c_1^*},\ d^*,\ e^*,\ f^*,\ \frac{g}{j,\frac{D/h}{D/i}},\ \frac{i}{h},\ k,\ \frac{m}{l},\ n^*,\ o^*\text{-}p^*,\ q^*,\ (r^*)$$

Area D (Table 6-2)

$$C/\frac{\frac{g}{j,h},\ \frac{\frac{l}{k}}{j,n}}{\frac{i}{m}}$$

The fragments that slope markedly along their length, suggesting a fluvial origin, are indicated by an asterisk. One fragment that does not slope markedly, B/s, nevertheless occurs just upvalley from the point in lower Strathearn where the lower postglacial terraces in general change from being estuarine features to being fluvial terraces: it is therefore included within the fluvial sector.

a) Raised shorelines

It was noted earlier (Chap.4) that the lower postglacial terraces of lower Strathearn occur at 5 distinct levels: 8.9-9.2 m, 5.8 m, 4.4-4.6 m, 3.7-4.0 m, and 2.8-3.2 m. The small fragments representing the highest level, B/d and B/g, are only 0.2 m below the front of the main carse, and they may be the result of fluvial dissection of the latter during the early stages of excavation of the Earn trench. Such an interpretation is consistent with the absence of equivalent features elsewhere. The 5.8 m feature is also probably a remnant of a higher level, isolated by dissection (Chap.4).

In the Area C part of the lower Tay valley (Chap.5), at least 3 levels are represented: 6.4 m, 4.1-4.6 m, and 2.7 m. Inspection of the shoreline diagrams (Figs.8.6 & 9.2) in comparison with lower Strathearn suggests that the 4.1-4.6 m category may include 2 levels although in the Tay valley they are not found one above the other in staircases as they are in Strathearn. In the area bordering the River Tay between Inchyra and Cairnie Pier (Chap.6), 5 conspicuous steps occur in a staircase below the main carse, their shoreline altitudesbeing as follows : 6.4 m, 5.3-5.5 m, 4.5 m, 3.4 m, and 1.4 m.

Putting together the evidence in the two valleys, it may be stated with reasonable certainty that 6 distinct levels are represented, of which the lowest is reclaimed land. The 5 raised shorelines are designated LC-1 to 5 (LC = Lower Carse), and their component fragments are as follows:

TABLE 9-4

LC-1	6.4 m	C/m, D/g, D/l	N = 22
LC-2	5.3-5.5 m	D/h, D/k	N = 14
LC-3	4.4-4.6 m	B/j, B/u, C/j, D/j, D/n	N = 31
LC-4	3.7-4.3 m	B/f, B/i, B/k, B/v, B/y, C/i, C/k, C/l	N = 36
LC-5	2.7-3.4 m	B/e, B/h, B/l, B/w, B/x, C/h, D/i	N = 61

Fragment B/t, at 5.8 m, may be a dissected remnant of either LC-1 or the main carse.

Of several fragments of land near the Earn-Tay confluence that is known to have been reclaimed, only one, D/m, was measured, and its altitude, 1.4 m, is somewhat lower than might be expected from consideration of the altitude of mean high water mark of ordinary spring tides (MHWMOST) in this area. This altitude is 2.8 m O.D. at Newburgh and 3.4 m at Perth (Hydrographic Department, Admiralty, 1963). As the mouth of the River Tay is nearer to Newburgh than to Perth, and allowing for the funnelling effect and the increasing fluvial influence towards Perth, it is likely that MHWMOST at Cairnie Pier is about 3.0 m. By analogy with the present-day shoreline features in northeast Fife and in the Forth (Chap.2), the altitude of the edge of the present mudflats should lie about 0.8-1.2 m lower than this. The surface of Mugdrum Island lies at such a level (Chap.4). The fact that D/m is rather lower is understandable, however, when account is taken of the reason for reclamation, which in this case was the prevention of further shore erosion (Chap.6), suggesting that tidal scour was operative at this locality.

Unfortunately, the extensive, dense reed-beds (which have in part been artificially planted and encouraged: Anon, 1797; Grierson, 1845; Melville, 1935) and the treacherous nature of the Tay mudflats prevented measurement of the present shoreline, so that information concerning the latter depends on Admiralty tidal information and on analogy with northeast Fife and the Forth. This information suggests that Shoreline LC-5 is a raised shoreline, even though some of its component fragments would be at least partly inundated at spring tides but for the protective dykes. However, the possibility cannot be entirely excluded that it includes a few fragments that are related to present sea level rather than to an earlier stage in displacement.

It is not possible to use the gradients of the shorelines identified above as a basis for correlating them with the scattered fragments farther east, for the valley data occur within a distance of less than 5 km on the shoreline diagrams and they depart little from a horizontal attitude within this distance (Figs.8.6 & 9.2). Other problems confronting attempts at correlation include the presence of 5 levels within an altitudinal band of only 4 m, and the fact that, as the features are confined within narrow trenches occupied by large rivers, their relationship to contemporary sea level may differ slightly compared with features in more open estuarine situations farther east. Gradients of best-fit lines would therefore be of very doubtful extrapolative value. Any assignment of the features east of Newburgh must therefore remain speculative, particularly in the case of the raised beaches bordering the Eden estuary, some 25 km east of the Earn-Tay confluence. A possible scheme assigns the highest post-main carse feature of the Eden estuary, A/c, to LC-1; fragments A/a and A/b to LC-3; B/b to LC-4; and B/a and B/c to LC-5. The calculated gradients of these shorelines are listed in Table 9-5. Since LC-2 consists of only 2 adjacent fragments, no gradient was calculated for it. Shoreline LC-5 does not depart significantly from a horizontal attitude, and the best-fit lines for LC-4 produce values of r that are much lower than usual for this type of data, because the gradient is so low in relation to the scatter of the data.

TABLE 9-5

Shoreline	N	W18°N-E18°S plane		W37°N-E37°S plane	
		Gradient m/km	r	Gradient m/km	r
LC-1	27	0.03	-0.930	0.04	-0.928
LC-2	14	-	-	-	-
LC-3	57	0.02	-0.869	0.02	-0.870
LC-4	42	0.03	-0.536	0.04	-0.639
LC-5	78	-	-	-	-

Lower carse levels are much more extensive in the western Forth area, where 3 raised estuarine flats, PG-2 to 4, have been identified below the main carse (Sissons, 1967a; Smith, 1968). The shorelines are respectively about $\frac{3}{4}$-$1\frac{1}{2}$ m, $3\frac{1}{2}$-$4\frac{3}{4}$ m, and $5\frac{3}{4}$-$7\frac{1}{4}$ m below the Main Postglacial Raised Shoreline, and it is likely that the lowest 2 have correlatives amongst the 5 Earn-Tay features. Precise correlation is impossible, but considering the altitudinal spacing of the shorelines, it seems reasonable to correlate PG-3 with LC-1 and PG-4 with LC-4 or 5. Shoreline PG-2 probably has no recognisable equivalent in the Earn and Tay valleys, where the highest identifiable post-main carse feature is some $3\frac{1}{2}$ m lower than the Main Postglacial shoreline. The gradients of PG-2 and 3 are 0.07 and 0.05 m/km respectively, and PG-4, like the lowest Earn-Tay feature, does not depart significantly from a horizontal attitude. PG-3 is probably about 4,000 years old, the base of peat resting on the slope between PG-2 and 3 having been dated as 4,120$\pm$105 years B.P. (Sissons, 1967a & personal communication).

b) <u>River terraces</u>

Upvalley from the raised estuarine flats discussed above, the lower postglacial terraces are of fluvial origin In the Earn valley, 2 levels occur in the fluvial sector at Bridge of Earn (fragments s & r), corresponding to Shorelines LC-4 and 5, but farther west, the evidence for more than one level is sometimes equivocal, and there is usually no clear morphological distinction between river terrace and present floodplain (Chaps. 4 & 5). It thus appears that the Lower Carse period of shoreline displacement did not have commensurate effects upvalley from Bridge of Earn, for 5 raised shorelines are represented by not more than 2 fluvial flats, including the present floodplain. The lowest terrace/floodplain of the Earn slopes downvalley from about 10 m O.D. near Forteviot (fragment C/f) to about 3¾ m at Bridge of Earn (B/r), 6½ km away, at an overall gradient of approximately 0.9 m/km. The downvalley profile (Figs. 8.6 & 9.2) is curvilinear, however, the gradient over the 3 km between Forteviot and Broombarns (C/c) being about 1.4 m/km, and between Broombarns and Bridge of Earn, about 0.7 m/km.

As stated earlier (Chap.5), only one fluvial flat occurs lower than the main carse in the Tay valley, comprising fragments n, o, p, and q. The heights are not plotted on the shoreline diagrams because the north-south trend of the part of the Tay valley in question would grossly distort the gradient. The terrace/floodplain slopes down from about 7½ m at Scone Palace (C/q) to about 3 m at Leitchill (C/n), a distance of 5 km, at an overall gradient of about 0.9 m/km.

4. General characteristics of the postglacial raised beaches

a) The nature of the sediments

(i) The non-carse facies occurs only in eastern Fife, southeast of Guard Bridge (Chap.3), where the Main Postglacial and lower raised beaches are composed of sand and shells, with occasional gravel, resting on a rock platform of at least lateglacial age. Platforms that are much older than the overlying raised beach deposits have been described from many parts of Scotland and Ireland (McCallien, 1937; Stephens, 1957; Walton, 1959; Stephens & Synge, 1965; McCann, 1966, 1968; Sissons, 1967a), and are usually regarded as being of much greater than lateglacial age.

In East Fife the Main Postglacial beach is sometimes overlain by blown sand, which accumulated during the relative fall of sea level from the Main Postglacial Raised Shoreline, when large areas of offshore sediments were exposed to deflation. Evidence of this is found in various parts of Scotland, as noted by Kirk (1957).

(ii) The carse facies occurs in all other parts of the area studied. The nature of the carse deposits has already been considered in some detail (Chaps.4 & 6). They consist of a mixture of clay and silt, occasionally with some fine sand, the coarser materials being more prominent in the Carse of Gowrie than elsewhere. They contain many plant remains, chiefly reeds, and include littoral shells in areas east of Errol, there being only one report of shells farther west, in Perth (Chap.5). The shells occur both in isolated lenticular beds and in a widespread layer of silty fine sand that stretches inland, at a depth of 4-5 m, for several hundreds of metres from the frontal bluff of the main carse.

This layer is the only major exception to the general homogeneity of the carse sediments. Its coarseness in comparison with most of the carse deposits suggests a break in the continuity of sediment accumulation, or at least a change in the environment of deposition. The fauna includes principally the common cockle (Cardium edule), Scrobicularia piperata, and small numbers of mussel (Mytilus edulis), Pecten sp., and other species (Buist, 1841; Jamieson, 1865). According to Buist (1841, p.33), the shells "have precisely the appearance of a recent cockle-bed", are "generally united ... by their hinges, and often partially filled with the relics of their former inhabitants ..., and have no appearance whatever of having been transported after death from the place in which they lived, grew, and perished".

In his studies of the present-day fauna of sandy and muddy intertidal areas in the Firths of Clyde and Forth, and at St. Andrews and Carnoustie, A.C. Stephen (1929a & b, 1930) found that Cardium edule is most common between $\frac{1}{4}$ and $\frac{1}{2}$ way up the shore from low water mark. Unless the tidal range was greater when the shell bed was formed than it is now (4.0 m range at spring tides, 2.4 m at neaps, at Newburgh; Hydrographic Department, Admiralty, 1963), this suggests that the altitude of HWMOST at the time the shells grew was no more than 2 m or so higher than the top of the shell bed, or about 7 m O.D., and that the contemporary shoreline altitude in the vicinity was no more than about 6 m, some $3\frac{1}{2}$-4 m lower than the Main Postglacial Raised Shoreline.

The presence of this shell bed suggests that the progress of the Main Postglacial transgression was interrupted by a period when the intertidal zone was virtually stationary for long enough for the beds to accumulate, and when the conditions of sedimentation were such that silty fine sand rather than silty clay was deposited in the littoral zone. The reason for the coarser materials is not clear. The idea that they might reflect higher discharges of the rivers flowing into the estuary does not explain why a similar layer of coarser material is not found in lower Strathearn.

A shell bed up to $2\frac{1}{2}$ km wide also underlies the lowest carse level (PG-4) in the Grangemouth area of the Forth carselands. Like the Carse of Gowrie layer, it probably relates to the Main Postglacial transgression, for oyster shells from it have been radiocarbon dated as 6,240$\pm$120 B.P. (Sissons, 1969), and a piece of buried wood from near the shell sample gave a date of over 7,500 B.P. (Sissons, personal communication).

Although the shell fauna of the carse deposits in general includes species that are still common around the Scottish shores, it is notable for the large size of some shells, particularly the oysters, and for the occurrence of Scrobicularia piperata, which is either rare or absent in the estuaries of eastern Scotland today, preferring slightly warmer seas. These observations confirm the view of D. Robertson (1877), working in western Scotland, and of Praeger (1892) in Northern Ireland, that the sea was slightly warmer during the Main Postglacial transgression than it is today, which agrees with the pollen evidence of warmer climate in late zone VI and in zone VIIa (Chap.1).

A conspicuous faunal difference between the Tay and Forth carselands is the absence in the former of remains of stranded whales, between 15 and 20 of which have been discovered in the Forth carse deposits, including one near the head of the former estuary (Clark, 1947; D.E. Smith, 1965). It is unlikely that this contrast can be adequately explained by chance of discovery alone, for there is no reason to believe that the Earn-Tay carselands have been any less thoroughly probed than those of the Forth by the excavation of claypits, the digging of drains, the sinking of wells, and the like. A possible explanation is that the rate of sedimentation was so rapid in the Earn-Tay area that the estuary quickly filled-in almost completely with sediment (except for narrow deep-water channels) at each stage in the transgression. This is consistent with the fact that the Earn-Tay carselands are overwhelmingly occupied by the main carse level, which is now more than 4 km across in the Carse of Gowrie, and has been even wider, for the frontal bluff has recently undergone severe erosion in places (Chap.6). The lower carse levels are almost totally confined to the relatively narrow trenches occupied by the Earn and Tay rivers. Such rapid accumulation of mudflats with very gentle transverse gradients (cf. $\frac{1}{4}$ m/km across the widest part of the Carse of Gowrie, Chap.6) would make it difficult for whales to gain access to the area of the present carselands.

b) Surface form and altitude

The surface of the carselands is much less dissected by valleys and gullies than the surfaces of the lateglacial raised beaches, and the variability of the height measurements along the shorelines is much smaller in the former case than in the latter. This lower scatter of the data, coupled with the much lower shoreline gradients, makes certain influences on shoreline altitude more readily recognizable in the carselands than on the lateglacial flats. One such influence is the rise in shoreline altitude in sheltered inlets and embayments, as noted previously; another is the tendency for shoreline altitudes to be lower than normal on narrow terrace fragments, as in the case of the Easter Kincaple and Edenside Main Postglacial shoreline fragments near Guard Bridge (Chap.3); and a third influence is the tendency for carse heights to be slightly higher than normal where the carse deposits are very thin. The last of these effects is clearly demonstrated by the Muirton-Muirhead Main Postglacial shoreline data (Table 4-3; Chap.4), which are shown by residual values from the linear trend surface (all data excluding carse embayment heights) to be as much as 0.5 m higher than the computed altitude of the fitted plane, with a mean residual value for the 16 heights of +0.2 m. The writer thought initially that differential compaction of the carse sediments, which would be minimal where the latter are very thin, causing higher shoreline altitudes than where the deposits are thicker, was the probable explanation of this effect. However, it is likely that most of the compaction, both of the carse deposits and of the sub-carse peat, had occurred by the time the sea began to recede from the Main Postglacial Raised Shoreline, and in the probable absence of thick surface peat over the carse deposits that would cause later compaction (see below), differential compaction is an inadequate explanation. A more likely explanation is simply that in places where the high tides only just covered a ledge or flat of older deposits, a thin veneer of mud would be deposited at a higher level than elsewhere along the shore. This effect probably contributed to the rise in altitude up shallow inlets, particularly in the case of the Kilspindie-Rait embayment heights (Chaps.6 & 8). In places where the carse deposits are very thin, the carse surface also tends to reflect irregularities in the sub-carse surface (e.g. line IV, Fig.6.4; Chap.6).

In some localities, including the areas north of Leuchars (Chap.3), near Netherton (Chap.4), and east of Castle Huntly (Chap. 6), the main carse is backed by a slight depression up to 0.5 m deep, making it necessary to take height measurements farther than usual from the backslope. In some cases, such depressions may mark the position of former tidal creeks, and in other cases, they may result from a great abundance of saltmarsh vegetation at and near the edge of the former mudflats, the subsequent decomposition of the vegetation over and around which the carse deposits accumulated resulting in a depression in the carse surface.

A major difference in present surface form between the Earn-Tay carselands and those of the western Forth area is the absence in the former of surface peat, which is still widespread in parts of the latter, particularly in the western part of the Carse of Stirling. Prior to the well-documented peat clearances of the 18th. and early 19th. centuries, most parts of the Forth carselands were covered by peat up to 6 m thick (D.E. Smith, 1965; Sissons, 1967a), and beneath two peat bogs in the western part of the Carse of Stirling, the carse deposits are completely absent, the growth of peat initiated in pre-carse times (forming the sub-carse peat) having locally kept pace with estuarine sedimentation throughout the Main Postglacial transgression (Sissons & Smith, 1965a).

There is no evidence of a widespread surface-peat cover ever having existed over the Earn-Tay carse deposits, despite frequent assumptions to the contrary. The only occurrences of surface peat at present are in pre-carse gullies near Leuchars and Glencarse (Chaps. 3 and 6). Historical evidence includes descriptions of the carselands at the end of the 18th. century (Sinclair, ed., 1791-8; J. Robertson, 1799), and also in medieval times, documents dating back to the 13th century providing evidence concerning the state of the carselands. These documents include the rental books (translated and edited by Rogers, 1879-80, and Easson, 1947) of the former Cistercian abbey at Coupar Angus, which maintained a grange in the heart of the Carse of Gowrie (at Grange, Fig.6.2), and the chartulary of Lindores Abbey (ed. Dowden, 1903), on the carse near Newburgh. All of these descriptions refer to the ill-drained state of the carselands, with pools of standing water, marshes, and the like, and to the ditches that were dug for drainage even in medieval times; but never to widespread surface peat. There are even a few references to the importation into the carselands of peat for use as fuel.

This lack of extensive surface peat in the Earn-Tay carselands contrasts so strongly with its present and former abundance in the Forth that it is necessary to seek a physical cause, for it is highly unlikely that pre-medieval man had either the technological capability or the economic motivation to undertake large-scale clearances. At present, any suggestion is speculative, but the western Forth carselands lie nearer to the centre of uplift than those of the Earn-Tay area, and therefore emerged earlier from the sea following the culmination of the Main Postglacial transgression, and it is possible that the cause is related to this fact. One possibility is that climatic conditions for the initiation of peat growth were more favourable when the Carse of Stirling emerged than when the Earn-Tay carselands emerged.

CHAPTER TEN

THE NATURE, RATE, AND PATTERN OF SHORELINE DISPLACEMENT

Introduction

This chapter considers the nature, rate, and pattern of lateglacial and postglacial shoreline displacement in the Earn-Tay-East Fife area and in the Tay-Forth region. It is convenient to begin by summarizing the salient points of the shoreline sequence elaborated in chapters 8 and 9.

1. The shoreline sequence

a) The Earn-Tay area and eastern Fife

The shoreline sequence is illustrated on a summary shoreline diagram in the W18°N-E18°S plane (Fig.10.1). For ease of comparison, all gradients referred to in this chapter are those calculated in this plane, unless otherwise stated. Four principal phases of displacement may be recognized, their salient characteristics being as follows.

(i) The pre-Perth Readvance phase includes 6 successively lower and in general less steeply inclined raised shorelines (EF-1 to 6) formed during recession of the ice margin across East Fife from the Aberdeen-Lammermuir Readvance limit. The gradient of the oldest shoreline (EF-1), formed while the eastern edge of the ice sheet lay near Anstruther, is

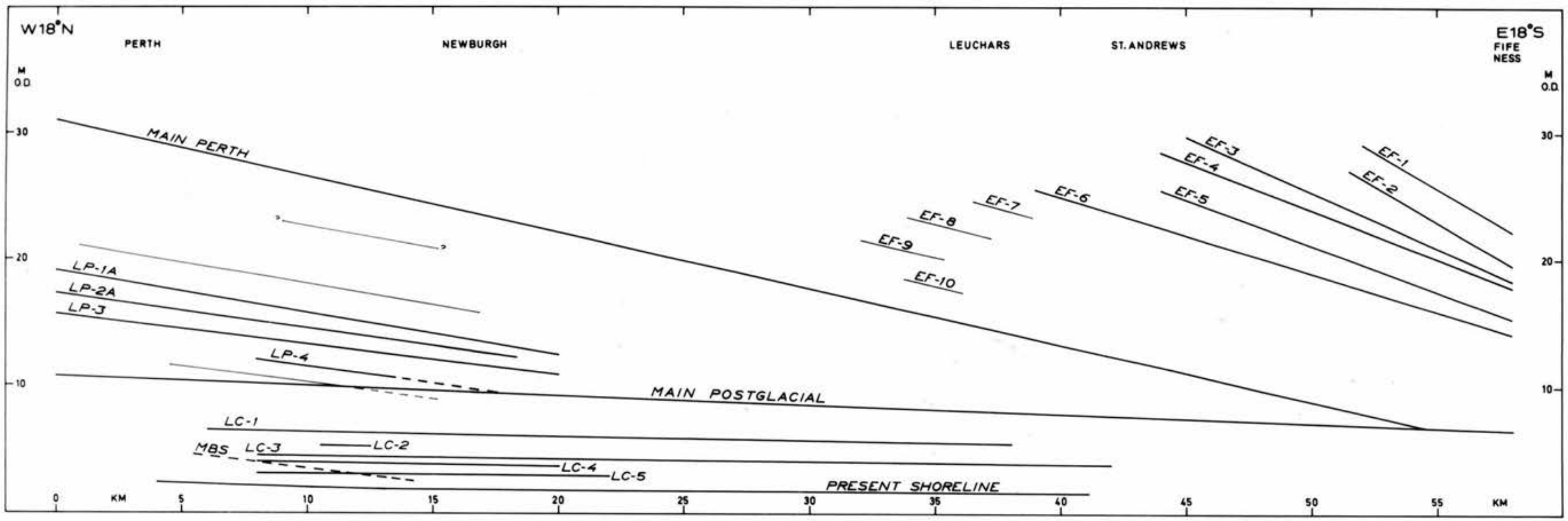


FIGURE 10.1 - Shoreline diagram (summary), Areas A-D: W18^{O}N-E18^{O}S plane. The thin lines represent shorelines on which the evidence is inadequate for the calculation of gradients. Of the buried features, only the Main Buried Shoreline (MBS) and the buried continuations of two lateglacial features are shown.

1.15 m/km, and that of the youngest (EF-6), formed when the ice margin lay near the sites of St. Andrews and Leven, is 0.59 m/km. Evidence for 4 lower and younger shorelines (EF-7 to 10) is confined to the vicinity of former wasting ice masses in the Wormit Gap and in the Leven valley, and meaningful gradients could therefore not be calculated. The further westward recession of the ice margin is recorded only by highly fragmented raised shoreline evidence, and all that can be said about shoreline gradient is that when relative sea level was at 26-27 m adjacent to the former ice margin near Newburgh, it was not above 17 m near Leuchars, suggesting a minimal gradient of almost 0.7 m/km. It is not known how far the ice wasted before moving forward again as the Perth Readvance.

(ii) The Perth Readvance phase includes evidence of at least 9 stages of shoreline displacement, the highest and most conspicuous shoreline being the Main Perth Raised Shoreline, which has a gradient of 0.45 m/km and was formed while the ice lay at or near the readvance limit. At least one subsequent stage is represented by 5 scattered shoreline fragments that lie $3\frac{1}{2}$-7 m below the Main Perth level, and the third stage, also represented by scattered data, is a shoreline about 2-$2\frac{1}{2}$ m above LP-1. Three fragements in East Fife (A/E_1, F_1, & M_1) belong to either the second or third stage. Shorelines LP-1 to LP-4 represent stages 4 to 7, and have gradients of between 0.35 and 0.25 m/km (although the W18°N-E18°S place is not the most appropriate for these features; Chap.8). LP-4 passes beneath the carse deposits in the Carse of Gowrie. Stage 8 includes 2 visible and some buried shoreline fragments, but the available evidence is not yet sufficient to warrant the calculation of shoreline gradient, and stage 9 is represented by only one buried terrace fragment as yet. The 5 Perth Readvance shorelines for which gradients could be calculated (the Main Perth and LP-1 to 4) show a consistent decrease in gradient with decreasing age and altitude when they are plotted in the most appropriate planes, from 0.43 to 0.21 m/km in the W7°N-E7°S plane, and from 0.44 to 0.24 m/km in the W13°N-E13°S plane.

Very little is known about the period that intervened between the wasting of the ice from the Perth Readvance limit and the onset of the Zone III Readvance, nor is it known how far deglaciation proceeded, although according to Sissons (1967a) it may have been complete. Particularly enigmatic in Scotland is the short cold phase (Zone 1c) that separated the Bølling and Allerød interstadials (Chap.1). The next piece of evidence relating to shoreline displacement is the buried gravel layer, which is thought to include 2 terraces of fluvial or fluvioglacial origin, one deposited when local relative sea level was 5 m or less, and the other when relative sea level was at or below O.D. It is not possible to date this layer more precisely than to say that it postdates the Lower Perth sequence, and predates the High

Buried Shoreline equivalent.

(iii) The Zone III Readvance phase is the least well documented. It includes 4 buried raised shorelines, the lowest of which has a gradient of about 0.26 m/km, was formed about 9,600 B.P. and is probably equivalent to the Main Buried Shoreline of the Forth carselands. It is likely that one of the 3 higher buried shorelines in lower Strathearn correlates with the High Buried Shoreline, formed while the ice lay at the Zone III Readvance limit, and that the whole sequence relates to the deglaciation that followed the attainment of this limit, which, in the Earn-Tay area, lies well inland of the raised shorelines. The lowest relative sea level reached in lower Strathearn during this period of negative shoreline displacement was lower than 0.9 m.

(iv) The Main Postglacial transgression and subsequent events. The period of low relative sea level just mentioned was followed by the Main Postglacial transgression, which was in progress between about 8,500 and 5,800 B.P. The transgression was probably interrupted by a period of stillstand during which a layer of sand and shells, now buried, accumulated in the Carse of Gowrie. The limit of the transgression is marked by the Main Postglacial Raised Shoreline backing the main carse level, both the shoreline and the associated estuarine flat being morphologically continuous over large parts of the area of study. The gradient of the shoreline is 0.07 m/km (0.09 m/km in the more appropriate W37°N-

E37°S plane), and its age about 6,000 years. Following the formation of the Main Postglacial shoreline, relative sea level fell, and 5 successively lower raised shorelines, LC-1 to LC-5, were formed. The second of these Lower Carse shorelines is confined to one small area, and the lowest does not depart significantly from a horizontal attitude. The gradients of the others are 0.03-0.02 m/km (0.04-0.02 m/km in the W37°N-E37°S plane). If the tentative correlation of LC-1 with PG-3 in the Forth area is correct, LC-1 is probably about 4,000 years old

The present shoreline was measured only in the Eden estuary and along the south shore of the Firth of Tay east of Tayport, for reasons that were explained earlier (Chap.9). The present edge of the mudflats and sandflats lies at 1.3-1.9 m, approximately 0.8 m below HWMOST (Chap.2). The altitude of the latter increases westwards up the Tay estuary and river, to 2.8 m at Newburgh and 3.4 m at Perth. It is reasonable to assume that the westward rise of former high water marks was no greater than this, and it may often have been less, because when relative sea level was higher than now, the estuary was broader, and the funnelling effect consequently less marked.

An early assumption made in this work (Chap.2) was that former shorelines may have borne a similar relationship to former high water marks to that borne by the present shoreline to present high water mark. The validity of this assumption cannot readily be tested. It depends partly on former tidal ranges being approximately similar to those of today, which may not have been strictly the case in view of the considerable changes in coastal configuration during lateglacial and postglacial times, and partly on sedimentation rates being sufficiently rapid to produce well-defined flats to near their maximal level before significant negative shore displacement occurred. At least the latter requirement was probably fulfilled, for sedimentation appears to have been rapid in both lateglacial and postglacial times (Chaps. 8 & 9).

b) Comparison with the Forth sequence

The shoreline sequence in the Forth area is summarized in Figure 10.2, although since this diagram was first published (Sissons, Smith, & Cullingford, 1966), knowledge of the Main Postglacial and buried raised shorelines (including the Buried Gravel Shoreline) has improved (Sissons, 1969, 1972). The East Fife sequence is common to both the Tay and Forth areas, although the later stages (EF-7 to 10) were omitted from the original diagram. As already indicated (Chaps. 8 & 9), agreement between the two areas is very close in respect of the Main Perth and Main Postglacial raised shorelines, but the Tay area has much more evidence of the Lower Perth sequence, and more shorelines in the Lower Carse sequence, although evidence of the latter (represented by PG-2 to 4, Fig. 10.2) is areally much more abundant in the Forth. There also appear to be more buried raised shorelines in the Tay area, but much less is known about them than in the Forth: the only Earn-Tay feature

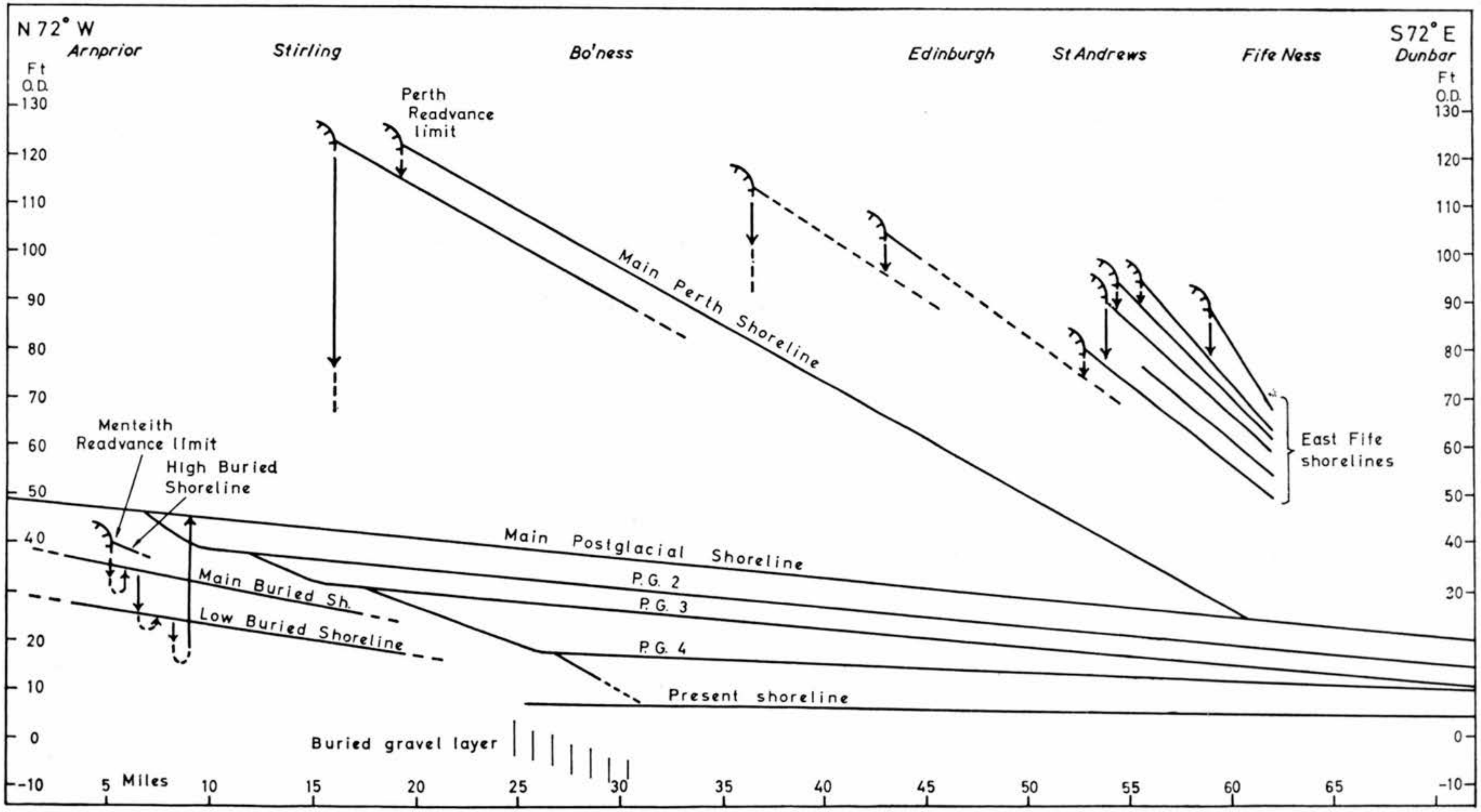


FIGURE 10.2 - Shoreline diagram (summary), the Forth area and eastern Fife: W18°N-E18°S plane (after Sissons, Smith, & Cullingford, 1966).

for which a gradient has been calculated (the Main Buried Shoreline ; 0.26 m/km) slopes more steeply than the equivalent feature in the Forth, but the latter is complicated by dislocation, so the difference may arise from this fact, or from the lack of data in the Earn-Tay area, or both.

2. The nature of the shoreline displacement

a) Isostatic forces

The evidence summarized above points to the existence of 17 distinct, tilted shorelines of lateglacial and postglacial age, all sloping down in directions between east and eastsoutheast, and generally declining less steeply with decreasing age. In addition, there are at least 12 stages of displacement for which there are insufficient data for the calculation of meaningful shoreline gradients, either because of lack of research (in the case of buried features), or because the evidence is confined to too small an area, or is too scattered. The lateglacial shorelines were formed while glacier ice occupied extensive tracts of Scotland, and several of them were formed in the proximity of wasting ice. The most likely explanation of these characteristics is that the shorelines were uplifted and deformed by differential isostatic recovery consequent upon deglaciation.

Differential isostatic rebound still occurs at directly measurable rates in Fennoscandia (Witting, 1918; Fromm, 1953; Kääriäinen, 1953, 1963; Bergsten, 1954) and in North America

(Gutenberg,1941; Moore,1948; Barnett,1966), and both the present deformation and the evidence of past deformation provided by raised shorelines have led to much discussion about the geophysical nature of isostatic depression and recovery (e.g. Niskanen,1939,1943,1949; Burgers & Collette, 1958; Heiskanen & Vening Meinesz,1958; Crittenden,1963a & b; Broecker,1966; Einarsson,1966; Walcott,1970). The main points of general agreement from this work may be summarized as follows.

Ice sheets (and large bodies of water) consitute loads sufficient to cause basinlike crustal subsidence, partly by elastic, but chiefly by plastic, deformation involving the subcrustal transfer of material away from the downwarped area to compensate for the extra load. The removal of this load by deglaciation (or by evaporation or decanting of the water body) results in a return flow of subcrustal material, causing updoming of the crust until recovery of the original profile is complete or nearly complete. Recovery is not instantaneous, but involves a time lag known as the relaxation time, usually defined as the length of time taken for the deviation from isostatic equilibrium to diminish to $\frac{1}{e}$ $(= \frac{1}{2.718})$ of its initial value. The crust has sufficient strength for the depression and recovery to extend a considerable distance beyond the edge of the ice sheet or water body, estimates for this distance varying from 50 km in the case of Pleistocene Lake Bonneville (Crittenden,1963b) to 300 km or more in the case of the Laurentide ice sheet

(Broecker, 1966; Walcott, 1970).

There are also several points of disagreement concerning the nature of isostatic deformation, including the reality or otherwise of a peripheral bulge beyond the depressed area; whether the dome of uplift is an expanding or a contracting one; and the magnitude of the forces and effects involved, including the effective viscosity of the earth, the relaxation time, and the minimum load required to depress the crust. Concerning the last point, there is a growing body of evidence (e.g. Bloom, 1967) that even relatively small loads such as shallow water bodies deform the crust. Many of these disagreements arise from incomplete geophysical knowledge of the forces and materials involved, but many result from the inadequacies of geomorphological and geological data used in the formulation and testing of the models of isostatic deformation.

As stated earlier (Chap. 7) the 2-dimensional form of isostatically uplifted raised shorelines has long been regarded as curvilinear. According to Broecker (1966) their form approximates closely to exponential (or nearly exponential) curves, while Andrews (1968a) considered that it is better described by power functions. In either case, the shape is thought to reflect primarily the rate of ice wastage, the degree of curvature being inversely proportional to the rate of glacier recession, and variations in the latter would cause deviations from the theoretical form. It is clear from both the Earn-Tay and Forth data that the degree of curvilinearity in eastern Scotland, although detectable on the Main Perth and Main Postglacial shorelines (Chaps. 8 & 9), is very slight. Furthermore, it might be the result of such factors as variable sedimentation rates rather than of deformation geometry.

An important aspect of glacioisostatic deformation revealed by the Tay-Forth raised shoreline data is the effect of lateglacial readvances. The Main Perth Raised Shoreline was formed at the culmination of the Perth Readvance (Chaps. 5 & 8), an event of sufficient magnitude to make its approximate contemporaneity with important readvances elsewhere almost certain. It is therefore reasonable to assume that the culmination of the readvance was contemporaneous with a low point on the eustatic sea-level curve (sec. 1b), so that if isostatic recovery of the land from its maximal depression had been continuous throughout the period of the readvance, the culmination of the latter should correlate with a very low relative sea level. In fact it correlates with the highest raised shoreline in the western parts of the Earn-Tay and Forth areas, a relationship that can only be satisfactorily explained by postulating considerable redepression of the earth's crust by Perth Readvance ice, as pointed out by Sissons and Smith (1965b). Similar reasoning applies to the contemporaneity of the High Buried Shoreline with the culmination of the Zone III Readvance, the latter also having caused renewed crustal depression (Sissons, 1966, 1969).

Several workers in Fennoscandia, Iceland, and North America have correlated major glacial advances with high relative sea levels, but relatively few (e.g. Thorarinsson,1951; Bloom,1963; Easterbrook,1963; Kaye & Barghoorn,1964; Andrews,1966; N.R. Page, 1968; Mörner,1969a & b) have specifically postulated either renewed crustal downwarping or significant retardation of uplift.

Renewed downwarping occasioned by glacial readvances is reflected in the sequential variation of shoreline gradients, and has important implications concerning the rate of isostatic response to loading and unloading. Thse matters are discussed below (sec.3).

In the western Forth area, the Main Buried Shoreline has been dislocated in 2 localities, by 1 m and nearly 1½ m respectively, and both the Main Buried and Main Postglacial shorelines slope in 3 areas and are horizontal in the 2 intervening areas, showing that "the widespread assumption that raised shorelines in areas of glacial rebound have uniform or very gradually changing gradients is not of universal application" (Sissons,1972). Sissons suggests that one of the dislocations may result from early postglacial movement along the Abbey Craig fault, and that the other, at the Menteith moraine, may have been caused by the weight of Zone III Readvance ice west of the moraine.

Dislocations and/or non-uniform uplift have also been postulated by Fennoscandian workers, including Sauramo (1939, 1947,1955a & b), von Post (1929,1947), and Mörner (1969a). The type of shoreline deformation postulated throughout

Fennoscandia by Sauramo is remarkably similar to that demonstrated by Sissons, but on a much larger scale. However, Sauramo's views have been heavily critized by Virkkala (1957,1959), Hyyppä (1963), and Nilsson (1953,1968,1970), all of whom have firmly rejected his shoreline correlations across the so-called hinge-lines. Nevertheless, a hinge-line in southern Sweden has recently been postulated by Mörner. Von Post claimed to have identified irregular uplift in Sweden, caused by faulting (1929) and by oscillatory uplift due to "elastic shocks" (1947), but his views too have been refuted by Nilsson, who claimed that uplift has been very regular in southern Sweden.

There is at present no evidence of dislocation or non-uniform uplift in the Earn-Tay-East Fife area, although the buried shoreline sequence has not yet been investigated sufficiently to be sure of its absence. The Main Postglacial shoreline shows a very consistent pattern of height variation throughout the area if the embayment heights are excluded (Chap.9), and the Main Perth Raised Shoreline, although exhibiting greater variability of altitude data than the Main Postglacial feature, nevertheless shows sufficient regularity of height variation to greatly limit the possible magnitude of any dislocations or abrupt changes in gradient in later features (Chap.8).

b) Eustatic sea-level changes

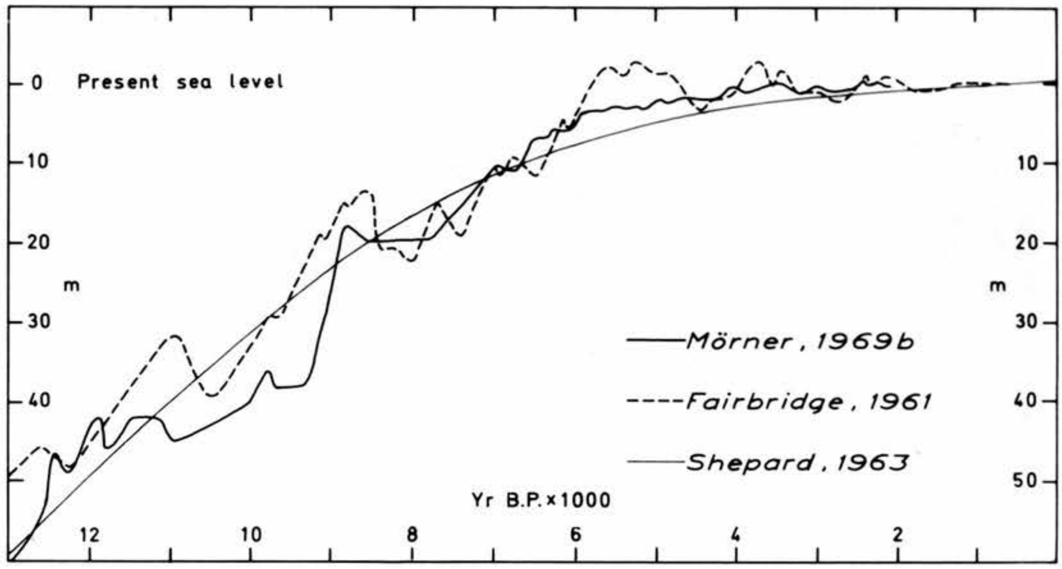
Despite a long history of study, and much recent, intensive work aided by many radiocarbon dates, it is not yet possible to present a definitive curve of eustatic sea-level changes over the last 17,000 years. Estimates for the altitude of world sea level (in relation to present sea level) at 17,000 B.P. range between -80 and -100 m. Since then the overall trend has been upward, owing to the return of water from the ice sheets to the oceans, but there are considerable disagreements about the nature and details of the overall eustatic rise.

Many discrepancies between different curves arise from the problems of relating dated samples to contemporary sea level, and from the different approaches used, of which the most important are: (i) the dating of organic materials that are thought to be fairly directly related to former world sea levels (e.g. Godwin, Suggate, & Willis, 1958; Fairbridge, 1961; Jelgersma, 1961, 1966; Shepard, 1963; Curray, 1965; Scholl & Stuiver, 1967; Scholl, Craighead, & Stuiver, 1969); and (ii) the separation of the eustatic and isostatic components of shoreline displacement in areas of glacioisostatic deformation, by comparing displacement at different localities (e.g. Sauramo, 1928; Schofield, 1964; Mörner, 1969a & b).

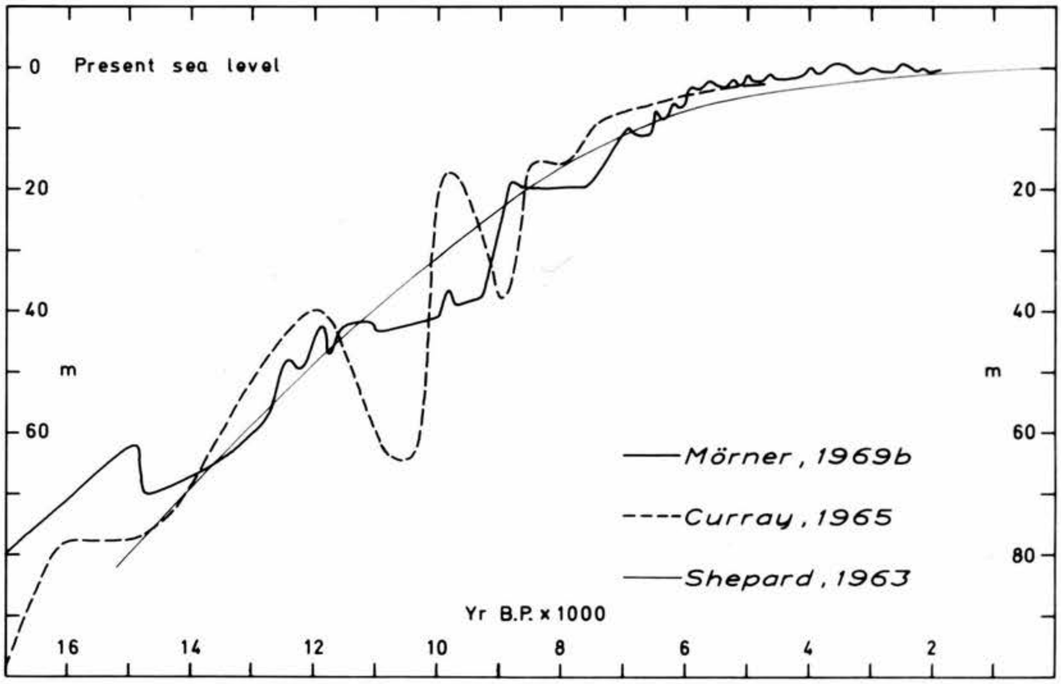
One problem involved in the first of these approaches is that most of the relevant organic materials are either buried or submerged (or both), which creates difficulties in establishing their relationship to contemporary sea level, especially in view of compaction of the sediments. Another problem is that of establishing the amount of tectonic movement that has occurred at the sites in question, for it is clear that few so-called "stable" areas are in fact stable (Jelgersma, 1966; see below). The most widely used curves based on this approach are those of Fairbridge (1961) and Shepard (1963).

The second method has the disadvantage that it relies on the validity of the shoreline correlations. Moreover, the need for a large area of study, to provide a sufficient range of intensity of isostatic recovery to allow accurate calculations of the eustatic component, conflicts with the need for detailed work to ensure valid shoreline correlations and dating. With detailed work, however, the problems of separating the eustatic and isostatic components are probably no greater than the difficulties of separating eustatic and non-eustatic components in areas not affected by glacioisostatic rebound, especially in view of the sensitivity of the crust to water loading postulated by Bloom (1967), which implies that " . . . coastal stability is a myth . . ." (Newman & Munsart, 1968, p.95). The most detailed work of this second type so far is that of Mörner (1969a) in southern Sweden and the Kattegatt.

Mörner's eustatic curve for the last 13,000 years is shown, together with those of Fairbridge and Shepard, in Figure 10.3A; and the curves of Shepard, Curray (1965), and Mörner for the last 17,000 years are compared in Figure 10.3B. It is evident that, whilst Shepard believed that world sea level rose smoothly to its present level, and that the considerable scatter of points on his graph reflects errors rather than oscillations (a view shared by Godwin, Suggate, & Willis, 1958; Jelgersma, 1961, 1966; and Scholl, Craighead, & Stuiver, 1969), Fairbridge, Curray, and Mörner proposed an oscillatory overall rise, involving a number of considerable regressions (a view shared by Schofield, 1964). Fairbridge's curve has been highly criticized for the



A



B

FIGURE 10.3 - Eustatic sea-level curves: A. 13,000 - 0 B.P. (after Mörner, 1969b); B. 17,000 - 0 B.P.

several errors it embodies (e.g. Shepard, 1963; Schofield, 1964; Mörner, 1969b), but according to Mörner (1971, p. 167), "worldwide climatic-eustatic oscillations are a reality, even during the Holocene, and . . . we will all, sooner or later, have to accept them." The amplitude of the oscillations suggested by Mörner, however, is much smaller than Fairbridge proposed.

There is considerable disagreement over the changes since 6,000 B.P.: Godwin et al., among others (listed in Jelgersma, 1966), suggested that present sea level was attained about 5,500 B.P., and has since remained steady; Shepard, Jelgersma, and Scholl et al., considered that the present level was reached only recently; and Fairbridge, Schofield, and Mörner, while disagreeing about the date present sea level was first attained, suggested that this level has been exceeded within the last 5,000 years. The maximal level postulated by Mörner (+0.4 m) is much lower than that of the other two workers.

The present trend of world sea level is upward, and tide-gauge and other data summarized by Gutenberg (1941), Jelgersma (1961), and Wexler (1961) indicate a contemporary eustatic rise of about 1 mm/yr.

c) The interplay of isostatic and eustatic factors

W.B. Wright (1914, 1936, 1937) and Ramsay (1924) explained lateglacial and postglacial shoreline displacement in terms of an interplay between isostatic land uplift and eustatic rise of sea level, regressions occurring when the rate of the former exceeded that of the latter, and transgressions occurring when eustatic rise was more rapid. Wright further stated that marked raised shorelines represent periods when land and sea were rising at the same rate, this being his 'isokinetic theory'. Although this theory seems tenable in some areas, including Scotland (D.E.Smith,1965; Synge & Stephens,1966), it is difficult to apply to the central parts of the areas formerly covered by the Fennoscandian and Laurentide ice sheets, where rates of uplift have always exceeded rates of eustatic rise, but where raised shorelines nevertheless occur.

As shown earlier (Chaps. 8 & 9) the Main Perth and High Buried raised shorelines mark the culmination of major transgressions. These were in progress during important glacial readvances that involved renewed isostatic downwarping of the earth's crust: an effect of isostatic depression outstripping eustatic fall that was not envisaged by Wright. Other transgressions, however, were the result of eustatic rise outstripping isostatic uplift, the principal one being the Main Postglacial transgression, which occurred during a period of rapid eustatic rise. It is reasonable to assume an equality of isostatic and eustatic rises at the time the Main Postglacial shoreline was formed, thus supporting the isokinetic theory. Since isostatic uplift was differential, being greater and faster in the central parts of the uplift area than near the periphery, it follows that the isokinetic balance represented by the shoreline should have occurred earlier in the western parts of the Tay-Forth region than in the east. It was stated earlier (Chap.7) that this effect might be detectable by radiocarbon dates in the later parts of the shoreline sequence, when both uplift rates and the standard deviations of dates had diminished. This appears to be the case, for whereas the Main Postglacial shoreline had already been abandoned by 6,500 B.P. in the western Forth carselands, it was only abandoned about 5,800 B.P. in northeast Fife (assuming that peat growth began on the carse surface as soon as the sea receded, as it did in the Forth area; Chaps. 7 & 9). Wright's suggestion that the major postglacial shoreline is younger in peripheral than in central parts of the uplifted area is therefore justified.

It is not always easy to ascertain whether the other raised shorelines are transgressive or regressive. There is no evidence to suggest a transgressive character for the pre-Perth Readvance shorelines (EF-1 to 10) in the sense of eustatic rise exceeding isostatic uplift (they are obviously partly transgressive in that they record the progressive inundation of formerly ice-covered tracts; Chap.8), but it is possible that they reflect periods of approximate isokinetic balance. In the case of the Lower Perth shorelines one might cite their sharpness and the extensive flats associated with them as evidence of a transgressive origin, or at least of distinct halts in the negative displacement. The early postglacial Main and Low buried shorelines are thought by Sissons (1966,1967a) to mark slight transgressions interrupting a 1,500-year period of negative displacement. Conversely, there is stratigraphic evidence that the Main Postglacial transgression may have been interrupted by a period of stable relative sea level (Chaps.6 & 9). Finally, the absence of sub-carse peat beneath the Lower Carse flats, and the present of the latter in the river-eroded Earn trench, suggest that at least the highest one (LC-1) marks the culmination of a transgression; and their conspicuous morphological clarity suggests that the later ones also are either transgressive or the result of distinct stillstands.

One may therefore conclude that the isostatic recovery of the crust from its maximal depression was punctuated by at least 2 periods of renewed downwarping, and that there have been at least 29 occasions (Figs.10.1 & 10.2) when there has existed a sufficient degree of relative shoreline stability to produce well-defined raised shorelines and associated depositional flats. At least some, and possible most, of the periods of balance occurred at the culminations of transgressions, and they need not have been prolonged in view of the rapidity of sedimentation that has been postulated throughout the sequence (Chaps. 8 & 9). They demonstrate fluctuations in the rate of either isostatic rise or eustatic rise, or (more probably) both, and it is much easier to interpret the sequence in terms of oscillatory eustatic curves than in terms of smooth ones (sec.2b).

Figure 10.4A shows the relative sea-level changes that have occurred since 13,000 B.P. at a point (10 km from the origin in the W18°N-E18°S plane) between Bridge of Earn and Abernethy. Altitudes of shorelines not represented at this point are derived by calculation from their overall gradients. A solid line is used for parts of the curve where both the probable age and the altitude of the shoreline(s) are known (assuming that the correlation of LC-1 with PG-3 in the Forth area is correct),

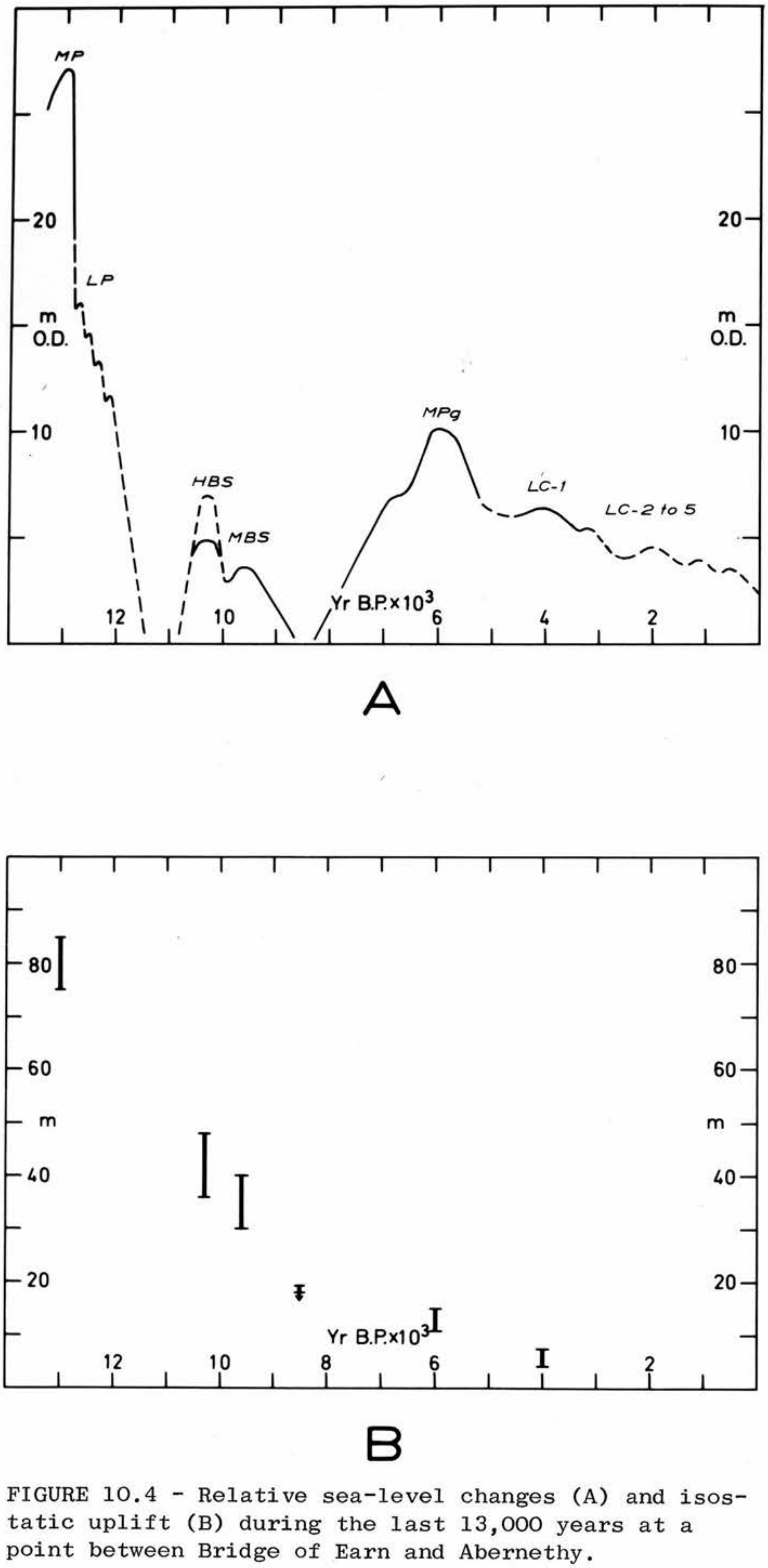


FIGURE 10.4 - Relative sea-level changes (A) and isostatic uplift (B) during the last 13,000 years at a point between Bridge of Earn and Abernethy.

and a broken line indicates a lack of reliable information on either age, or altitude, or both, these parts of the curve being wholly schematic (e.g. the age of the High Buried Shoreline is known, but its altitude lies between 4.9 & 6.9 m; the altitudes of LP-1 to 4 and LC-2 to 5 are known, but not their ages; and neither the age nor the altitude of the relative sea level(s) contemporaneous with the buried gravel layer is known, except within broad limits).

In view of the complexity of the isostatic-eustatic relationships, and the uncertain accuracy of eustatic curves, one cannot make definitive comparisons between Figure 10.4A and the eustatic curves (Fig.10.3A). Nevertheless, it may be noted that the Main Buried, Main Postglacial, and LC-1 shorelines all correspond fairly closely with transgressions on Mörner's curve, and, slightly less closely, on Fairbridge's curve. The suggestion of multiple postglacial transgressions may also be compared with recent evidence in southern Sweden, where 6 transgressions have been identified between 7,000 and 3,800 B.P. (Berglund, 1971).

d) Other factors affecting shoreline displacement

Although there is little doubt that shoreline displacement in the Tay-Forth region is largely the net effect of glacio-isostatic deformation and eustatic changes, other factors may have made minor contributions, including the following.

(i) Offshore water loading. Bloom(1967) suggested that the load of water added to the continental margins by the lateglacial and postglacial rise of world sea level has been sufficient to isostatically deform coastal areas in proportion to the average depth of water in the vicinity, even when relatively small depths of water were involved. It is not possible to cite any evidence from the Earn-Tay-East Fife area either for or against this hypothesis, but it has found strong support from other workers, including Newman and Munsart (1968) and Mörner (1969a & b). Mörner has proposed the term 'hydro-isostasy' for the process.

(ii) Long-term tectonic movements. The southern parts of the North Sea basin has been undergoing slow, tectonic subsidence since Mesozoic times (Bennema, 1954; Godwin, Suggate, & Willis, 1958; Jelgersma, 1961), and although the areal extent of this downwarping is not known, it is a possible contributor to shoreline tilting in the Tay-Forth region.

3. The rate of displacement

The dearth of absolute dates and the uncertainties about the eustatic changes make it difficult to obtain reliable quantitative data on rates of displacement and uplift in the Earn-Tay-East Fife area, but consideration of the relationship between shoreline movement and ice decay permit qualitative assessments to be made, during both the 'pre-Perth' and Perth Readvance periods of displacement.

Shorelines EF-1 to EF-6 were formed while the ice margin receded a distance of only 15-25 km (Chaps. 3 & 8). Even if one were to postulate a slow rate of ice recession, the period of time available for the formation of these shorelines is therefore only a small proportion of that covered by the whole sequence of Figures 10.1 and 10.2, yet EF-1 and EF-2, the steepest shorelines in the whole sequence, have a gradient (1.15-1.16 m/km) about twice that of EF-6 (0.59 m/km). When it is taken into account that 4 later and lower shorelines (EF-7 to 10, for which meaningful gradients could not be calculated) were formed before the ice margin had receded much further, one may conclude that more than half the overall isostatic tilting that East Fife has undergone since shorelines EF-1 and EF-2 were formed occurred during deglaciation of the area. Furthermore, there is morphological evidence of rapid ice decay, particularly in the southern part of East Fife, where low-lying kettles show that some buried ice masses outlasted the formation of shorelines EF-1 to EF-6, and probably EF-7 and EF-8 too (D.E.Smith,1965; Cullingford & Smith, 1966). The clear implication is that the isostatic uplift that accompanied deglaciation was immediate and rapid, which contradicts Wright's assumption of slow initial recovery (1936,1937).

Rapid initial recovery is also suggested by the Perth Readvance period of displacement (Chaps. 5 & 8). While the ice lay at or near the readvance limit, relative sea level in Strathearn fell from 32 m (the local altitude of the Main Perth Raised Shoreline) to less than 23 m (the height of the lower end of outwash terrace 5/7; Figs.8.6,8.8, & 8.9), a negative displacement of more than 9 m. Since world sea level was probably rising at the same time in response to deglaciation, the actual land uplift during this short period was probably greater than this. Furthermore, the descent of proglacial meltwater channels in the Tay valley to about the extrapolated level of shoreline LP-4 suggests a relative fall in sea level while the ice still lay near the readvance limit of at least 17 m. It is therefore probable that at least the Main Perth and LP-1 to LP-4 shorelines were formed while the ice margin receded only a short distance, and therefore during a short period of time, for the ice decay following the culmination of the readvance was probably quite rapid (Sissons, 1967a). The changes of gradient in the Perth Readvance shoreline sequence confirm the rapidity of the initial recovery after the crustal redepression, the gradient of the Main Perth shoreline (0.43-0.45 m/km according to the plane of projection) being about twice that of LP-4 (0.21-0.28 m/km). Rapid uplift following the Perth Readvance maximum is confirmed by evidence in the Forth area (Sissons & Smith, 1965b), where the minimum initial displacement demonstrated by the field evidence is even greater than that just described.

Figure 10.4B is a graph of uplift since 13,000 B.P. at the same point as that used for Figure 10.4A. It shows the net amount of uplift that has occurred since each specified date, each value being the sum of the present altitude of a raised shoreline and the overall eustatic rise since the shoreline was formed. The length of the bar representing each control point reflects the range of estimates of eustatic sea level (Fig. 10.3), and assessment of the effect of crustal redepression or uplift retardation caused by the Zone III Readvance is prevented by lack of dates of the preceding Lower Perth shorelines. The graph is therefore both overgeneralized and very approximate, but it serves to demonstrate that the rate of uplift was greatest immediately after deglaciation, and has declined progressively towards the present, as shown by workers in other areas (e.g. Feyling-Hanssen & Olsson, 1959; Olsson & Blake, 1961; Washburn & Stuiver, 1962; Andrews, 1970).

The progressive decline in the rate of uplift can be demonstrated in a general way by comparing postglacial shoreline gradients in the Tay area. The gradient and date of the Main Buried Shoreline, so far as is known at present, are 0.26 m/km and about 9,600 B.P. respectively; those of the Main Postglacial Raised Shoreline are 0.09 m/km (in the W37°N-E37°S plane) and about 6,000 B.P.; and those of shoreline LC-1 are 0.04 m/km (W37°N-E37°S) and about 4,000 B.P. The present-day shoreline has an estimated gradient of 0.02 m/km. The approximate mean rates of tilting for 3 consecutive periods of postglacial time are therefore as follows:

9,600-6,000 B.P.	0.047 m/km/yr x 10^3
6,000-4,000 B.P.	0.025 m/km/yr x 10^3
4,000- 0 B.P.	0.005 m/km/yr x 10^3

Several workers have noted that the rate of decline of shoreline gradients is an exponential function of time, and A.Grønlie (1941, 1947, 1964) used this relationship as a dating device, whereby the known ages and gradients of 2 or more shorelines may be used to estimate the ages of other shorelines in the same sequence, provided that their gradients are known. This technique was further tested and developed by Norrman (1964) and Dahl (1968), who showed that ages calculated by this means compare closely with radiocarbon ages.

Andrews and Dugdale (1970) have attempted to apply the technique to the Tay-Forth data, using the gradients and ages of the Main Postglacial, Main Buried, and Main Perth raised shorelines (as given in Sissons, Smith, & Cullingford, 1966; & Sissons, 1967a) to estimate the ages of shorelines EF-1 to EF-6. The calculated ages cover the range 18,250-15,100 B.P. Unfortunately, not only have the age of the Main Postglacial and the gradients of the Main Buried and EF-1 shorelines been shown by later work to differ somewhat from the values used by Andrews and Dugdale, but also the use of the Main Perth and 2 postglacial shorelines to calculate the ages of the pre-Perth sequence must be considered invalid in view of the crustal redepression probably caused by the Main Perth and Zone III readvances (sec.2a). Considering the long period of over 3,000 years which, according to Andrews and Dugdale, covered the formation of EF-1 to EF-6 (implying a very slow rate of ice recession that is at variance with the field evidence), and the likelihood that they were formed after 17,000 B.P. (Chaps. 1 & 8), it is, of course, possible that one or more of the shorelines date from the time period stated above; but the valid application of this method of dating to the pre-Perth sequence would require radiocarbon dates on at least 2 members of that sequence. Similarly, its use in the Perth Readvance sequence would require dates for at least 2 members of the Main Perth-Lower Perth sequence. Even then, the method assumes a regular decline in the rate of uplift that may not always have occurred (e.g. Mörner, 1969a & b, demonstrated irregularities in the relationship of gradient to time in southern Sweden), and an additional problem is that raised shorelines are time transgressive, so that a range of ages may be applicable to one feature. Nevertheless, given adequate dating control within a sequence from which evidence of significant glacier readvances and irregularities of uplift is absent, the method can give reasonable approximations of the ages of raised shorelines.

Finally, comparison of shoreline gradients may demonstrate the effect of readvances in redepressing or temporarily retarding the recovery of the crust. For example, the difference in gradient (0.13 m/km) between shorelines EF-5 and EF-6, which were formed within a short time period while the ice margin receded only a few kilometres, is about the same as that (0.14 m/km) between EF-6 and the Main Perth shoreline, which are separated by a much longer time period during which the ice margin receded at least 60 km (the laminated clays immediately predating the readvance having been found at least as far west as Crieff; Chap.5), and probably much further (Sissons, 1964a), and then moved forward again to the Perth Readvance limit. The Main Perth shoreline is thus more tilted in relation to its age than is EF-6, adding further support to the idea that the readvance caused renewed crustal depression. The same reasoning may be used in the case of the Main Buried Shoreline, formed after the Zone III Readvance: the shoreline gradient (0.26 m/km, although this value is based on minimal information) being similar to that of LP-4 (0.24 m/km in the most appropriate plane), despite the much greater age of the latter.

4. The pattern of displacement

The isobases of the Main Perth and Main Postglacial raised shorelines in the Tay-Forth region (Chaps. 8 & 9) show a marked difference that has important implications concerning the nature and pattern of displacement.

The Main Perth isobases swing slightly northwards in the Tay area as compared with the Forth (Fig.8.7), the directions of slope of the linear surfaces for the two areas being E7°S and E13°S, and the gradients 0.43 and 0.42 m/km respectively. As stated previously (Smith, Sissons, & Cullingford, 1969), these results may in part reflect limitations in the field evidence in the eastern parts of the areas, but they are in accord with what has previously been said of the form of isostatic uplift in Scotland. The dome of isostatic uplift has long been assumed to be approximately elliptical with its major axis lying roughly north and south (Wright, 1937). Areas about the minor axis of the ellipse should therefore have the steepest shoreline gradients, sloping, in eastern Scotland, towards the east. With increasing distance from the minor axis, shoreline gradients should diminish and, in eastern Scotland, the direction of slope should have a diminishing eastward component. In terms of these considerations, the trend surfaces depicted in Figure 8.7 are consistent with the Tay-Forth region being located a short distance south of the minor axis of the ellipse.

The Main Postglacial isobases, by contrast, swing markedly eastwards in the Tay area compared with the Forth, the directions of the linear surfaces being E37°S and E13°S, and their gradients

0.09 and 0.08 m/km. respectively. This contrast is brought out clearly by the quadratic and cubic surfaces for the Tay-Forth region (Fig.9.4). Thus, while in the Forth area the Main Perth and Main Postglacial isobases are almost exactly parallel, their trends in the Tay area differ by 30°, a difference that is highly unlikely to reflect local variations in sediment supply, or non-uniform uplift (Chap.9; sec.2a). It may reflect either a northward shift in the centre of uplift since the Perth Readvance, or the development of a second centre to the north or northeast of the first one. In this connection it is interesting to note the possibility suggested by Sugden (1970) that in Zone III, the Cairngorms were largely submerged beneath a much greater thickness of ice than that envisaged by Sissons (1967a).

Changing centres of uplift during shoreline displacement, which have also been demonstrated in Fennoscandia (e.g. Lundqvist, 1965), seriously undermine the concept of shoreline relation diagrams (Chap.7), whose use in Scotland has been advocated by Synge and Stephens (1966, 1967), although Synge (1969) has since recognized their shortcomings in his work in Norway. This supports the writer's earlier statement (Chap.7) that the type of displacement implied by the use of relation diagrams requires to be demonstrated rather than assumed. In view of the dislocation and non-uniform uplift of some shorelines demonstrated by Sissons (1972), the irregular variations in the rate of uplift demonstrated by Mörner (1969a), the renewed crustal depression occasioned by glacier readvances, and changes in the location of centres of uplift just discussed, it must be concluded that any method of studying shoreline displacement that assumes great regularity in the crustal response to unloading must be considered suspect until such regularity has been convincingly demonstrated for the area concerned.

Another aspect of the pattern of displacement, arising from the isostatic-eustatic interplay, is the intersection of shorelines. For example, lower members of the Lower Perth sequence intersect the Main Postglacial shoreline in the eastern part of the Carse of Gowrie, where they almost certainly continue eastwards as buried features; and Figure 10.1 shows that even the best-fit line of the Main Perth shoreline, the highest lateglacial shoreline in the western parts of the region, intersects that of the Main Postglacial shoreline near Fife Ness. The best-fit lines of shorelines EF-1 to EF-6, if projected without change of gradient towards E18^{o}S, intersect each other east of Fife Ness, the lowest (EF-6) becoming the highest about 25 km out, and if the zone of intersection is projected west of south in the approximate direction of the isobases, it intersects the coast of part of East Lothian in which the lateglacial shoreline sequence is so confused that it has not yet been resolved (Sissons, 1967a). It seems likely that the confusion may result from the intersection of the shorelines.

CHAPTER ELEVEN

CONCLUSION

The investigation described above has resulted in the recognition of at least 29 stages of lateglacial and postglacial shoreline displacement, 17 of which are represented by raised shoreline fragments that are sufficiently numerous to allow meaningful gradients to be calculated, and the other 12 by distinct features that are either insufficiently studied (in the case of buried features), or are too localised or too scattered, to warrant the calculation of gradients. Of the 17 shorelines whose gradients were calculated, 16 slope down towards directions between east and southeast, and in general their gradients decline with decreasing age. Four phases of displacement may be recognized as follows.

(i) The pre-Perth Readvance phase. 10 shorelines were formed during the deglaciation of eastern Fife after the Aberdeen-Lammermuir Readvance. The gradients of the highest and oldest 6 shorelines (EF-1 to 6), which rise to 23-29 m O.D. at their western ends, range from 1.16 to 0.59 m/km (in a W18^{o}N-E18^{o}S plane). Scattered shoreline evidence marks the further westward ice recession in the Tay basin.

(ii) The Perth Readvance phase. 9 shorelines were formed at and soon after the culmination of the Perth Readvance. The slopes of the 5 features whose gradients were calculated (the Main Perth and LP-1 to 4 shorelines) decline progressively from 0.44 to 0.24 m/km (W13^{o}N-E13^{o}S plane). The Main Perth shoreline reaches a height of 32 m O.D. at its western end, and the highest altitudes on LP-1 to 4 range from 15 to 19 m. Relative sea level in the lower Earn and Tay valleys fell to 0 m O.D. or less at some time after the Lower Perth sequence and before the culmination of the Zone III Readvance.

(iii) The Zone III Readvance phase. The culmination and subsequent ice wastage of the Zone III Readvance are correlated with a sequence of 4 buried raised shorelines about which little is known in the Earn-Tay area. The best-known (the Main Buried Shoreline) has a gradient of about 0.26 m/km (W18°N-E18°S), and was formed about 9,600 B.P.

(iv) The Main Postglacial and later phase. Relative sea level in lower Strathearn fell after the formation of the buried raised beaches to less than 0.9 m O.D., and then rose to the culmination of the Main Postglacial transgression. The Main Postglacial shoreline, which is virtually continuous over large parts of the area of study, has a maximal altitude in the west of $11\frac{1}{2}$ m O.D., and a gradient over the whole area of 0.09 m/km (W37°N-E37°S plane). It was formed about 6,000 B.P. Five later and lower raised shorelines are largely confined to the lower Earn and Tay valleys: the gradient of LC-2 was not calculated, that of LC-5 is not significantly different from horizontal, and those of LC-1, 3, and 4 are 0.04-0.02 m/km (W37°N-E37°S).

The shorelines have been uplifted and tilted by glacioisostatic recovery, which began as soon as deglaciation started, and was very rapid at first. The recovery from the maximal ice load of the last glaciation was not continuous, but was interrupted by renewed crustal depression caused by the Perth and Zone III readvances, one result being that shoreline gradients do not decline in strict proportion to their age. The rate of uplift has declined progressively during postglacial time. Many, possibly most, of the shorelines are transgressive, and the sequence is most readily explained in terms of oscillatory eustatic rise and fluctuating rates of isostatic uplift.

The isobases of the 2 most prominent raised shorelines (the Main Perth and Main Postglacial), as determined by trend-surface analysis, differ so markedly as to suggest a significant shift in the centre of uplift after the Perth Readvance, thus demonstrating the invalidity, in the Earn-Tay-East Fife area at least, of the assumption underlying the use of shoreline relation diagrams.

Whilst the writer believes that the present investigation provides a more accurate and more meaningful picture of lateglacial and postglacial shorelines and shoreline displacement than was available before, it is apparent that much remains to be done, in both the geomorphological and other spheres. The major gap in geomorphological and stratigraphic knowledge undoubtedly concerns the buried beach sequences, and many more carseland bores are needed to provide an adequate knowledge of the lateglacial and postglacial buried beaches. A serious weakness in present knowledge is the dearth of dating information, and there is plenty of scope for pollen analytical, varve, and radiocarbon dating (although suitable material for the latter has proved elusive so far, at least in the lateglacial deposits). It is also probable that microfaunal and sedimentological studies would yield worthwhile information concerning environments of deposition. Finally, it is possible that a re-examination of the evidence of early man associated with the postglacial beach deposits might prove worthwhile in the light of the work described in this thesis, and of future work such as that suggested above.

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APPENDIX I

The following list contains all heights on terraces and related features levelled for this investigation, and gives the reference number (Ref.) by which each height is identified in the text and tables, its altitude (Alt.) in metres above Ordnance Datum, its National Grid reference (G.R.) and the closing error (C.E.) of the traverse. The closing error is in feet.

AREA A

Ref.	Alt. m O.D.	G.R. (All NO)	C.E. ft	Ref.	Alt. m O.D.	G.R. (All NO)	C.E. ft
A. 1	5.9	6224 1051	+0.02	A. 31	7.5	4978 1672	-0.01
2	6.7	6205 1064	"	32	7.5	4989 1666	"
3	6.7	6197 1070	"	33	7.4	4997 1665	"
4	6.4	6215 1058	"	34	4.9	4994 1685	"
5	6.7	6201 1067	"	35	6.6	5015 1666	0.00
6	6.3	6100 1130	0.00	36	6.8	5005 1663	"
7	6.4	6107 1126	"	37	5.1	5002 1682	"
8	5.8	6116 1128	"	38	5.6	5013 1680	"
9	6.7	6098 1133	"	39	6.0	5026 1682	"
10	6.2	6097 1139	"	40	7.7	4950 1683	-0.04
11	7.3	6057 1184	-0.06	41	7.7	4952 1682	"
12	6.4	6050 1189	"	42	7.9	4956 1680	"
13	6.6	6040 1196	"	43	7.5	4959 1678	"
14	6.7	6032 1203	"	44	5.1	4963 1687	"
15	6.0	6029 1215	"	45	7.1	4931 1709	"
16	6.2	6024 1227	"	46	4.8	4931 1726	+0.10
17	5.7	6023 1239	"	47	4.8	4939 1722	"
18	8.4	6007 1254	-0.01	48	3.6	4876 1757	+0.02
19	8.0	6003 1259	"	49	4.0	4886 1755	"
20	7.1	5992 1273	"	50	4.1	4895 1753	"
21	7.7	5986 1277	"	51	4.1	4905 1750	"
22	8.0	5981 1282	"	52	4.1	4913 1744	"
23	8.0	5977 1285	"	53	4.2	4878 1768	"
24	8.3	5970 1293	"	54	4.0	4870 1770	-0.05
25	8.7	5967 1299	"	55	3.5	4866 1758	"
26	8.8	5962 1304	"	56	3.3	4857 1761	"
27	5.5	4969 1686	"	57	3.1	4843 1768	"
28	5.6	4976 1685	"	58	4.0	4855 1778	"
29	7.3	4964 1676	"	59	3.5	4853 1773	"
30	7.5	4970 1673	"	60	4.0	4851 1761	"

A. 61	3.9	4847	1765	-0.05
62	9.7	4836	1761	"
63	3.3	4828	1771	"
64	3.5	4822	1767	"
65	3.5	4813	1768	"
66	3.6	4805	1770	"
67	3.6	4796	1773	"
68	3.9	4789	1773	"
69	3.9	4781	1776	"
70	3.8	4774	1780	"
71	6.7	4769	1774	"
72	7.0	4773	1772	"
73	6.9	4777	1769	"
74	6.9	4782	1768	"
75	4.1	4766	1782	"
76	4.0	4760	1786	"
77	4.0	4755	1792	"
78	22.1	6093	1104	+0.01
79	22.0	6086	1107	"
80	21.4	6080	1112	"
81	21.1	6075	1115	"
82	21.2	6068	1119	"
83	21.3	6062	1123	"
84	21.4	6055	1126	"
85	21.5	6049	1129	"
86	23.2	6059	1115	"
87	22.9	6066	1113	"
88	22.6	6072	1111	"
89	21.5	6085	1110	"
90	24.0	6086	1102	"
91	14.7	6244	1045	=0.02
92	14.7	6249	1041	"
93	14.7	6252	1035	"
94	14.4	6256	1030	"
95	14.5	6260	1025	+0.02
96	17.1	6247	1016	"
97	17.0	6252	1010	"
98	16.8	6258	1004	"
99	17.1	6264	1000	"
100	17.4	6242	1025	"
101	17.6	6238	1030	=0.01
102	21.6	6216	1025	"
103	21.7	6210	1030	"
104	22.3	6205	1036	"
105	24.9	5659	1463	-0.08
106	24.7	5651	1467	"
107	24.7	5643	1471	"
108	24.9	5635	1474	"
109	25.3	5626	1477	"
110	25.1	5618	1480	"
111	25.8	5612	1483	"
112	26.3	5605	1485	"
113	26.4	5599	1491	-0.08
114	21.2	5668	1477	"
115	21.6	5681	1474	"
116	21.2	5699	1472	"
117	7.6	5703	1491	"
118	7.4	5708	1491	"
119	7.5	5717	1493	"
120	7.6	5713	1492	"
121	21.4	5705	1471	"
122	21.4	5710	1468	"
123	9.7	5739	1488	-0.08
124	9.7	5745	1486	"
125	9.8	5751	1482	"
126	9.7	5758	1478	"
127	9.8	5765	1474	"
128	8.3	5746	1496	"
129	7.9	5753	1493	"
130	7.3	5758	1489	"
131	6.5	5766	1484	"
132	6.7	5768	1480	"
133	8.5	4653	2138	-0.09
134	8.7	4656	2131	"
135	8.4	4650	2146	"
136	8.1	4647	2153	"
137	7.9	4643	2161	"
138	8.1	4637	2169	"
139	7.8	4587	2207	+0.02
140	7.7	4580	2209	"
141	8.0	4546	2222	"
142	7.9	4543	2214	+0.02
143	8.1	4539	2207	"
144	8.2	4548	2229	"
145	8.3	4548	2237	"
146	8.2	4550	2244	"
147	8.0	4551	2252	"
148	8.2	4554	2260	"
149	8.3	4558	2266	"
150	8.4	4561	2273	"
151	8.8	4564	2275	"
152	8.3	4561	2285	"
153	8.4	4560	2293	"
154	8.4	4559	2300	"
155	8.4	4560	2308	"
156	8.4	4561	2316	"
157	8.4	4560	2324	"
158	8.4	4559	2332	"
159	8.5	4558	2338	"
160	8.5	4558	2343	"
161	8.3	4560	2352	"
162	8.4	4559	2359	"
163	8.4	4557	2367	"
164	8.3	4554	2374	"

A.	165	8.1	4548	2380	+0.02
	166	8.4	4549	2387	"
	167	8.2	4557	2427	-0.01
	168	8.3	4557	2414	"
	169	8.2	4556	2408	"
	170	8.2	4558	2436	"
	171	8.2	4558	2443	"
	172	8.2	4559	2451	"
	173	8.4	4564	2460	"
	174	8.6	4565	2468	"
	175	8.6	4566	2475	"
	176	8.4	4566	2482	"
	177	10.3	4543	2468	"
	178	10.6	4542	2461	"
	179	10.7	4540	2454	"
	180	15.7	4501	2443	"
	181	15.6	4495	2437	"
	182	15.9	4491	2431	"
	183	15.9	4487	2426	"
	184	15.6	4482	2420	"
	185	23.1	4473	2170	+0.03
	186	22.8	4473	2175	"
	187	23.1	4469	2189	"
	188	23.1	4469	2192	"
	189	22.8	4473	2191	"
	190	22.3	4470	2199	"
	191	15.6	4509	2221	-0.02
	192	15.7	4507	2229	2
	193	15.5	4505	2237	2
	194	15.7	4504	2244	2
	195	15.8	4503	2251	2
	196	15.8	4501	2257	2
	197	19.8	4420	2356	-0.19
	198	20.0	4417	2357	"
	199	20.0	4421	2359	"
	200	20.0	4423	2365	"
	201	20.0	4426	2373	"
	202	19.7	4427	2376	"
	203	19.9	4430	2381	"
	204	20.0	4433	2386	"
	205	20.1	4434	2392	"
	206	20.4	4436	2398	"
	207	20.8	4435	2402	"
	208	20.9	4439	2408	"
	209	20.4	4444	2413	"
	210	18.0	4447	2387	"
	211	17.6	4446	2380	"
	212	17.7	4444	2375	"
	213	16.3	4457	2371	"
	214	16.3	4455	2365	"
	215	16.4	4453	2359	"
	216	16.2	4459	2376	"
A.	217	16.1	4462	2382	-0.19
	218	16.1	4464	2388	"
	219	16.2	4466	2395	"
	220	16.1	4468	2403	"
	221	16.0	4471	2408	"
	222	16.1	4473	2414	"
	223	8.4	4565	2451	-0.01
	224	8.5	4565	2445	"
	225	8.7	4567	2440	"
	226	8.3	4570	2434	"
	227	8.9	4571	2430	"
	228	8.1	4567	2426	"
	229	8.5	4563	2490	"
	230	8.4	4560	2495	"
	231	8.6	4565	2515	"
	232	8.7	4565	2522	"
	233	8.5	4566	2528	"
	234	8.6	4571	2534	"
	235	8.6	4575	2540	"
	236	8.5	4574	2546	"
	237	8.5	4570	2553	"
	238	29.9	4459	2164	+0.03
	239	30.3	4456	2159	"
	240	29.7	4455	2152	"
	241	29.2	4456	2145	"
	242	28.4	4458	2138	"
	243	27.7	4459	2132	"
	244	27.0	4460	2124	"
	245	26.1	4438	2149	"
	246	25.5	4442	2141	"
	247	25.2	4441	2136	"
	248	26.5	4436	2154	"
	249	32.5	4460	2174	"
	250	35.8	4434	2181	"
	251	35.7	4438	2191	"
	252	35.8	4445	2197	"
	253	35.8	4447	2205	"
	254	35.8	4447	2213	"
	255	35.1	4439	2210	"
	256	35.7	4432	2214	"
	257	35.7	4423	2217	"
	258	36.0	4431	2220	"
	259	36.0	4427	2230	"
	260	36.3	4421	2235	"
	261	36.3	4421	2241	"
	262	35.8	4433	2224	"
	263	22.3	4410	2370	-0.05
	264	22.6	4408	2375	"
	265	22.1	4403	2369	"
	266	22.5	4398	2364	"
	267	22.8	4414	2380	"
	268	22.6	4418	2385	"

A.	269	22.9	4424	2391	-0.05
	270	23.1	4427	2395	"
	271	22.6	4431	2399	"
	272	21.1	4452	2421	"
	273	20.1	4453	2418	"
	274	19.8	4450	2413	"
	275	19.6	4458	2421	"
	276	19.2	4460	2427	"
	277	19.0	4465	2431	"
	278	18.7	4471	2436	"
	279	18.5	4477	2441	"
	280	17.9	4483	2446	"
	281	17.9	4487	2449	"
	282	15.5	4518	2518	0.00
	283	15.7	4517	2524	"
	284	15.8	4516	2530	"
	285	16.3	4516	2533	"
	286	24.5	6214	1016	+0.11
	287	24.5	6209	1021	"
	288	24.5	6205	1027	"
	289	24.8	6201	1032	"
	290	22.1	6190	1049	+0.21
	291	22.3	6187	1053	"
	292	22.1	6184	1058	"
	293	22.2	6182	1063	"
	294	22.4	6179	1067	"
	295	26.2	6162	1073	"
	296	26.4	6158	1077	"
	297	26.7	6154	1081	"
	298	21.7	6207	1035	+0.11
	299	21.5	6212	1028	"
	300	24.2	6219	1012	"
	301	23.5	5927	1271	+0.01
	302	23.2	5927	1279	"
	303	22.5	5929	1285	"
	304	22.2	5930	1292	"
	305	22.2	5935	1281	"
	306	21.8	5939	1274	"
	307	23.3	5926	1262	"
	308	23.3	5927	1255	"
	309	23.3	5932	1251	"
	310	22.8	5941	1254	"
	311	23.2	5942	1245	"
	312	23.0	5945	1240	"
	313	22.0	5964	1220	"
	314	21.3	5967	1226	"
	315	21.0	5968	1234	"
	316	20.8	5964	1239	"
	317	21.0	5959	1244	"
	318	21.2	5954	1249	"
	319	21.4	5948	1254	"
	320	21.9	5943	1259	"
A.	321	21.5	5941	1268	+0.01
	322	21.5	5944	1262	"
	323	18.1	5956	1286	"
	324	18.0	5951	1291	"
	325	18.0	5946	1296	"
	326	17.9	5942	1302	"
	327	17.3	5940	1307	"
	328	17.3	5937	1312	"
	329	17.5	5933	1319	"
	330	17.5	5930	1326	"
	331	17.5	5928	1333	"
	332	17.3	5925	1340	"
	333	16.9	5919	1346	"
	334	17.7	5960	1281	"
	335	17.5	5964	1277	"
	336	17.5	5968	1272	"
	337	17.4	5972	1265	"
	338	17.3	5978	1258	"
	339	17.4	5982	1252	"
	340	17.6	5987	1247	"
	341	17.6	5993	1241	"
	342	17.4	5998	1235	"
	343	25.4	5978	1157	+0.02
	344	26.4	5986	1147	+0.02
	345	26.2	5992	1141	"
	346	26.1	5998	1138	"
	347	25.8	6001	1138	"
	348	25.9	6006	1136	"
	349	25.4	6014	1132	"
	350	25.9	6019	1128	"
	351	25.1	5973	1162	"
	352	24.9	5957	1180	"
	353	24.9	5953	1185	"
	354	25.1	5948	1191	"
	355	22.5	5977	1184	"
	356	22.8	5968	1196	"
	357	22.5	5964	1204	"
	358	21.9	5967	1203	"
	359	21.6	5974	1193	"
	360	22.9	5893	1316	0.00
	361	22.8	5900	1314	"
	362	22.8	5908	1315	"
	363	22.9	5916	1311	"
	364	22.3	5923	1308	"
	365	22.5	5931	1306	"
	366	22.2	5931	1298	"
	367	27.0	5913	1290	"
	368	27.3	5909	1293	"
	369	26.9	5902	1296	"
	370	23.4	5886	1322	"
	371	22.6	5884	1329	"
	372	22.7	5883	1337	"

A.	373	22.9	5874	1340	0.00	A.	425	28.9	5110 1552	-0.03
	374	23.0	5866	1342	"		426	29.0	5104 1550	"
	375	25.1	5863	1322	"		427	29.2	5097 1548	"
	376	24.8	5865	1310	"		428	29.6	5091 1547	"
	377	25.1	5860	1302	"		429	29.2	5084 1546	"
	378	6.8	5838	1428	"		430	29.6	5077 1545	"
	379	7.5	5836	1430	"		431	31.0	5069 1545	"
	380	7.6	5834	1431	"		432	17.3	4353 2909	+0.40
	381	6.3	5839	1427	"		433	17.4	4351 2909	"
	382	5.2	5843	1425	"		434	17.4	4349 2909	"
	383	5.8	5852	1421	"		435	17.6	4347 2908	"
	384	7.4	5862	1424	"		436	17.6	4345 2908	"
	385	8.4	5867	1421	"		437	17.9	4343 2908	"
	386	8.1	5878	1420	"		438	17.7	4341 2907	"
	387	8.0	5883	1419	"		439	17.9	4339 2907	"
	388	19.7	5819	1392	"		440	8.5	4359 2921	"
	389	19.6	5813	1395	"		441	8.1	4357 2921	"
	390	19.7	5806	1398	"		442	8.0	4354 2920	"
	391	23.9	5773	1362	+0.01		443	7.9	4351 2920	"
	392	24.0	5772	1368	"		444	7.4	4348 2919	"
	393	24.2	5769	1374	"		445	7.7	4345 2919	"
	394	24.4	5763	1379	"		446	7.4	4342 2918	"
	395	24.2	5757	1384	"		447	1.6	4857 1827	-0.31
	396	28.4	5383	1542	-0.01		448	1.6	4860 1830	"
	397	28.1	5386	1541	"		449	2.0	4862 1830	"
	398	28.4	5389	1540	"		450	1.7	4862 1831	"
	399	28.2	5392	1539	"		451	1.5	4860 1836	"
	400	28.1	5395	1539	"		452	1.3	4858 1841	"
	401	27.6	5398	1539	"		453	1.2	4856 1845	"
	402	28.3	5401	1538	"		454	1.2	4853 1850	"
	403	28.5	5380	1543	"		455	1.2	4851 1854	"
	404	28.8	5375	1545	"		456	1.1	4849 1859	"
	405	28.1	5371	1547	"		457	1.0	4847 1864	"
	406	22.2	5208	1574	"		458	0.9	4845 1868	"
	407	22.1	5212	1574	"		459	1.6	4864 1831	"
	408	22.1	5217	1575	"		460	1.7	4868 1832	"
	409	22.0	5221	1576	"		461	1.7	4873 1832	"
	410	21.8	5225	1577	"		462	1.7	4877 1834	"
	411	27.9	5209	1566	"		463	1.7	4881 1837	"
	412	28.2	5213	1566	"		464	1.6	4885 1836	"
	413	28.4	5216	1567	"		465	1.6	4888 1840	"
	414	22.4	5204	1573	"		466	1.6	4890 1844	"
	415	22.8	5198	1573	"		467	1.7	4894 1847	"
	416	27.7	5165	1558	-0.03		468	2.0	4896 1850	"
	417	28.5	5169	1560	"		469	1.8	4898 1855	"
	418	27.0	5160	1556	"		470	2.0	4899 1859	"
	419	27.2	5153	1555	"		471	1.7	4852 1827	"
	420	26.5	5146	1555	"		472	1.7	4848 1827	"
	421	26.7	5137	1554	"		473	1.7	4844 1824	"
	422	28.1	5130	1555	"		474	2.4	4859 1824	"
	423	27.8	5121	1554	"		475	2.5	4862 1826	"
	424	28.2	5116	1553	"		476	6.6	4594 1887	+0.02

A.	477	6.6	4599	1890	+0.02	A.	529	34.4	4484 2543	-0.08
	478	6.8	4590	1887	"		530	33.9	4493 2543	"
	479	6.8	4585	1887	"		531	34.5	4466 2544	"
	480	7.0	4580	1886	"		532	35.0	4449 2543	"
	481	7.0	4575	1886	"		533	34.5	4461 2556	"
	482	7.2	4571	1886	"		534	35.5	4461 2568	"
	483	1.5	4597	1910	"		535	35.1	4469 2569	"
	484	1.4	4593	1911	"		536	34.9	4476 2571	"
	485	1.5	4590	1913	"		537	35.2	4439 2544	"
	486	1.5	4585	1915	"		538	35.1	4439 2547	"
	487	1.6	4581	1914	"		539	35.1	4434 2546	"
	488	1.6	4577	1915	"		540	35.4	4429 2547	"
	489	1.6	4576	1919	"		541	35.6	4425 2548	"
	490	1.6	4573	1923	"		542	35.9	4414 2548	"
	491	1.6	4568	1924	"		543	35.7	4413 2552	"
	492	1.7	4564	1924	"		544	35.9	4406 2550	"
	493	1.8	4559	1922	"		545	36.2	4402 2553	"
	494	1.8	4556	1920	"		546	36.8	4399 2557	"
	495	1.7	4551	1921	"		547	36.9	4396 2562	"
	496	2.5	4590	1908	"		548	36.9	4394 2567	"
	497	2.4	4596	1905	"		549	36.8	4401 2565	"
	498	1.5	4600	1907	"		550	35.8	4411 2570	"
	499	1.4	4605	1905	"		551	35.4	4423 2577	"
	500	1.5	4609	1902	"		552	36.6	4203 2327	+0.23
	501	1.4	4613	1899	"		553	36.2	4203 2334	"
	502	1.4	4617	1897	"		554	36.3	4203 2342	"
	503	16.2	4533	2617	+0.42		555	36.6	4203 2349	"
	504	16.5	4534	2623	"		556	37.3	4203 2354	"
	505	16.7	4536	2633	"		557	37.0	4196 2348	"
	506	17.0	4541	2643	"		558	36.9	4196 2339	"
	507	15.7	4547	2654	"		559	37.1	4196 2343	"
	508	15.3	4548	2649	"		560	38.2	4195 2354	"
	509	15.5	4548	2642	"		561	38.1	4187 2346	"
	510	15.4	4548	2634	"		562	38.3	4186 2339	"
	511	16.8	4551	2659	"		563	38.4	4178 2348	"
	512	16.0	4554	2665	"		564	38.6	4171 2350	"
	513	16.0	4555	2673	"		565	38.4	4171 2345	"
	514	16.8	4548	2673	"		566	38.2	4171 2340	"
	515	17.0	4551	2682	"		567	38.0	4162 2340	"
	516	18.8	4537	2693	"		568	38.8	4164 2346	"
	517	18.7	4532	2700	"		569	39.4	4162 2352	"
	518	34.7	4482	2577	-0.08		570	40.3	4161 2358	"
	519	34.4	4484	2573	"		571	40.1	4160 2365	"
	520	34.0	4491	2576	"		572	40.0	4155 2365	"
	521	33.9	4496	2578	"		573	40.1	4150 2364	"
	522	33.8	4503	2581	"		574	40.6	4136 2362	"
	523	33.9	4504	2565	"		575	40.4	4132 2360	"
	524	34.1	4498	2570	"		576	40.4	4129 2352	"
	525	34.3	4491	2569	"		577	40.4	4132 2353	"
	526	34.6	4482	2569	"		578	40.1	4137 2353	"
	527	33.8	4479	2555	"		579	40.0	4142 2354	"
	528	34.4	4475	2544	"		580	40.1	4146 2355	"

A. 581	40.0	4151	2356	+0.23	A. 632	36.8	4975	1549	+0.12
582	39.7	4156	2357	"	633	36.7	4971	1550	"
583	39.4	4152	2351	"	634	37.0	4965	1550	"
584	39.3	4144	2345	"	635	26.2	6056	1111	+0.03
585	39.6	4136	2338	"	636	26.1	6052	1113	"
586	39.9	4170	2356	"	637	26.0	6047	1115	"
587	39.7	4178	2356	"	638	26.1	6042	1116	"
588	39.4	4186	2355	"	639	23.8	6056	1117	"
589	39.7	4186	2367	"	640	23.8	6051	1119	"
590	39.7	4177	2367	"	641	24.1	6047	1120	"
591	39.7	4169	2367	"	642	33.7	6051	1098	"
592	32.1	5029	1547	+0.12	643	33.6	6047	1099	"
593	32.5	5033	1547	"	644	33.7	6043	1100	"
594	32.1	5038	1546	"	645	41.5	6058	1076	"
595	32.2	5042	1546	"	646	41.2	6063	1074	"
596	32.0	5047	1545	"	647	41.2	6068	1072	"
597	31.4	5052	1545	"	648	41.1	5984	1086	-0.02
598	25.0	4814	1748	-0.09	649	41.0	5980	1091	"
599	25.2	4821	1747	"	650	41.9	5933	1105	0.00
600	25.4	4828	1742	"	651	42.3	5932	1101	"
601	24.1	4836	1740	"	652	42.9	5932	1097	"
602	24.0	4844	1739	"	653	25.7	5921	1204	"
603	24.0	4828	1745	"	654	25.5	5923	1203	"
604	25.3	4808	1749	"	655	25.5	5924	1202	"
605	25.5	4801	1750	"	656	20.2	5378	1555	"
606	26.7	4793	1750	"	657	20.1	5373	1557	"
607	27.3	4786	1752	"	658	21.3	5368	1560	"
608	27.6	4779	1753	"	659	21.8	5365	1563	"
609	28.3	4765	1754	"	660	21.3	5370	1559	"
610	28.8	4759	1755	"	661	20.6	5367	1552	"
611	29.5	4749	1755	"	662	29.0	5368	1547	-0.09
612	28.8	4742	1756	"	663	28.7	5363	1549	"
613	30.5	4735	1755	"	664	28.1	5359	1552	"
614	30.8	4727	1754	"	665	28.6	5354	1554	"
615	31.0	4719	1755	"	666	29.2	5352	1553	"
616	30.9	4713	1756	"	667	35.2	5338	1544	"
617	33.0	4605	1805	"	668	35.0	5343	1542	"
618	33.6	4609	1800	"	669	35.1	5348	1541	"
619	33.6	4614	1796	"	670	35.4	5353	1539	"
620	33.7	4620	1791	"	671	35.4	5357	1538	"
621	32.2	4632	1800	"	672	35.7	5362	1536	"
622	32.2	4637	1797	"	673	26.8	5597	1490	+0.10
623	30.4	4641	1782	"	674	27.6	5593	1493	"
624	30.7	4646	1777	"	675	27.0	5589	1495	"
625	30.7	4649	1771	"	676	26.7	5585	1497	"
626	35.3	5008	1544	+0.12	677	26.5	5582	1499	"
627	35.5	5003	1544	"	678	25.5	5579	1503	"
628	35.9	4999	1545	"	679	20.2	5622	1501	"
629	36.3	4994	1546	"	680	19.4	5618	1503	"
630	36.3	4987	1547	"	681	19.9	5614	1506	"
631	36.6	4979	1548	"	682	26.2	5603	1487	"

A. 683	25.6	5609	1486	+0.10	A. 735	24.2	5601	1499	-0.02
684	26.3	5608	1485	"	736	23.9	5601	1504	"
685	25.2	5615	1483	"	737	33.3	4401	1880	+0.01
686	19.5	5881	1360	+0.09	738	33.5	4396	1876	"
687	19.4	5886	1359	"	739	33.6	4390	1871	"
688	19.5	5891	1358	"	740	33.8	4384	1868	"
689	19.6	5895	1355	"	741	33.8	4377	1865	"
690	19.2	5900	1353	"	742	33.9	4374	1860	"
691	19.2	5904	1351	"	743	33.2	4396	1884	"
692	19.7	5877	1361	"	744	33.5	4388	1891	"
693	19.7	5872	1363	"	745	33.0	4373	1886	"
694	19.4	5867	1364	"	746	32.9	4365	1885	"
695	19.3	5863	1366	"	747	32.9	4358	1885	"
696	20.0	5858	1367	"	748	33.1	4351	1884	"
697	19.1	5906	1346	"	749	33.5	4345	1882	"
698	9.6	4715	1842	0.00	750	33.5	4337	1881	"
699	9.7	4710	1843	"	751	33.6	4330	1879	"
700	9.7	4705	1844	"	752	33.7	4323	1875	"
701	9.4	4700	1845	"	753	34.0	4318	1871	"
702	9.6	4695	1847	"	754	34.0	4313	1866	"
703	10.0	4691	1849	"	755	34.2	4310	1861	"
704	9.8	4686	1850	"	756	40.8	3626	1226	+0.05
705	10.0	4681	1851	"	757	41.9	3627	1219	"
706	10.2	4674	1859	"	758	39.9	3636	1251	"
707	10.3	4675	1864	"	759	39.6	3632	1244	"
708	39.0	4433	2741	-0.02	760	39.6	3643	1257	"
709	40.2	4428	2735	"	761	39.8	3645	1261	"
710	43.1	4411	2721	"	762	39.5	3649	1265	"
711	38.9	4451	2755	"	763	38.9	3661	1277	"
712	37.0	4456	2770	"	764	38.3	3674	1287	"
713	34.9	4463	2778	"	765	38.2	3693	1302	"
714	34.4	4469	2783	"	766	1.4	4524	1857	+0.02
715	33.2	4474	2788	"	767	1.3	4524	1862	"
716	32.7	4479	2793	"	768	1.3	4513	1852	"
717	32.1	4484	2798	"	769	1.3	4507	1850	"
718	17.9	6074	1139	-0.04	770	1.2	4501	1850	"
719	18.1	6069	1143	"	771	2.4	4504	1846	"
720	18.3	6065	1146	"	772	2.4	4511	1847	"
721	18.0	6079	1136	"	773	3.8	4514	1842	"
722	17.8	6083	1132	"	774	4.0	4510	1840	"
723	11.5	5777	1463	+0.01	775	3.8	4505	1837	"
724	11.2	5780	1460	"	776	4.0	4500	1836	"
725	19.0	5767	1441	"	777	4.0	4496	1828	"
726	19.3	5770	1436	"	778	4.2	4491	1830	"
727	19.8	5773	1429	"	779	4.1	4486	1830	"
728	19.1	5776	1432	"	780	4.1	4481	1829	"
729	18.5	5765	1445	"	781	4.3	4478	1828	"
730	18.4	5761	1449	"	782	5.7	4538	1826	"
731	24.0	5756	1436	"	783	5.5	4530	1824	"
732	24.2	5611	1493	-0.02	784	5.5	4522	1828	"
733	24.6	5606	1495	"	785	5.6	4514	1829	"
734	24.4	5604	1499	"	786	5.5	4505	1828	"

A. 787	8.1	4545	1819	+0.02		A. 839	39.1	3897	1399	-0.01
788	8.1	4537	1816	"		840	39.0	3904	1402	"
789	8.0	4530	1814	"		841	38.6	3902	1405	"
790	8.1	4522	1811	"		842	38.2	3895	1403	"
791	8.3	4514	1810	"		843	39.0	3887	1401	"
792	8.1	4506	1808	"		844	39.6	3856	1385	"
793	35.2	4487	1788	+0.08		845	39.4	3860	1387	"
794	34.9	4492	1790	"		846	38.6	3864	1388	"
795	34.9	4496	1791	"		847	40.6	3847	1376	"
796	33.6	4501	1793	"		848	34.3	3843	1385	"
797	33.1	4506	1793	"		849	34.7	3838	1381	"
798	33.3	4511	1793	"		850	35.0	3829	1375	"
799	33.5	4516	1793	"		851	31.0	4490	2805	-0.02
800	32.9	4521	1793	"		852	27.2	4502	2810	"
801	34.3	4470	1784	"		853	23.7	4520	2821	"
802	34.3	4465	1783	"		854	24.3	4514	2816	"
803	33.7	4459	1781	"		855	24.8	4509	2813	"
804	33.7	4454	1779	"		856	30.8	4922	1620	+0.04
805	34.0	4449	1778	"		857	31.7	4914	1623	"
806	34.3	4444	1777	"		858	32.2	4907	1627	"
807	34.3	4439	1775	"		859	32.4	4900	1631	"
808	34.3	4434	1773	"		860	32.6	4894	1639	"
809	33.9	4430	1772	"		861	32.8	4886	1642	"
810	34.6	4425	1771	"		862	33.6	4877	1647	"
811	34.9	4421	1771	"		863	36.4	5004	1532	+0.12
812	25.7	4409	1806	"		864	35.9	5011	1532	"
813	26.8	4406	1798	"		865	36.3	5018	1532	"
814	27.0	4397	1793	"		866	36.6	5023	1532	"
815	27.4	4391	1787	"		867	36.5	5027	1532	"
816	26.9	4384	1780	"		868	36.4	5032	1533	"
817	6.9	4455	1820	"		869	20.5	4295	2506	-0.03
818	6.7	4447	1820	"		870	20.6	4288	2506	"
819	6.9	4440	1819	"		871	20.7	4281	2506	"
820	8.2	4455	1811	"		872	20.8	4274	2506	"
821	9.0	4449	1810	"		873	21.0	4266	2505	"
822	5.7	4491	1819	"		874	21.2	4258	2503	"
823	6.1	4484	1817	"		875	21.3	4251	2502	"
824	6.2	4477	1817	"		876	21.4	4245	2500	"
825	6.5	4469	1818	"		877	21.4	4237	2499	"
826	6.6	4462	1819	"		878	21.5	4229	2497	"
827	8.4	4518	2016	+0.03		879	21.3	4224	2494	"
828	8.0	4526	2016	"		880	21.5	4217	2491	"
829	8.3	4534	2015	"		881	21.6	4210	2488	"
830	7.9	4541	2015	"		882	21.7	4223	2465	"
831	8.0	4550	2015	"		883	21.6	4231	2461	"
832	8.5	4479	1967	+0.01		884	19.4	4339	2390	-0.02
833	8.5	4471	1965	"		885	19.2	4342	2383	"
834	8.5	4463	1962	"		886	19.0	4345	2377	"
835	8.2	4455	1962	"		887	19.7	4347	2371	"
836	8.3	4447	1967	"		888	20.9	4315	2385	"
837	38.3	3883	1393	-0.01		889	21.1	4309	2382	"
838	38.4	3890	1396	"		890	21.1	4302	2380	"

A. 891	21.6	4296	2379	-0.02
892	27.6	4359	2366	"
893	27.6	4358	2360	"
894	27.4	4357	2355	"
895	27.9	4384	2320	"
896	28.3	4379	2322	"
897	28.5	4374	2324	"
898	28.8	4368	2325	"
899	28.7	4364	2326	"
900	29.4	4318	2369	"
901	29.4	4313	2368	"
902	34.8	4243	2316	"
903	34.7	4236	2320	"
904	35.5	4228	2323	"
905	36.3	4219	2323	"
906	35.6	4228	2335	"
907	36.2	4226	2345	"
908	36.4	4228	2359	"
909	36.2	4236	2361	"
910	36.9	4228	2365	"
911	38.3	4214	2376	"
912	35.4	4239	2345	"
913	36.3	4232	2345	"
914	21.9	4290	2379	"
915	21.6	4283	2383	"
916	22.9	4383	2345	0.00
917	22.7	4378	2342	"
918	22.5	4374	2338	"
919	1.6	4683	2791	"
920	1.6	4691	2790	"
921	1.6	4698	2786	"
922	1.7	4678	2794	"
923	1.6	4676	2801	"
924	1.5	4672	2808	"
925	1.5	4668	2814	"
926	2.4	4691	2785	"
927	1.7	4713	2785	-0.01
928	1.6	4721	2782	"
929	1.7	4728	2779	"
930	1.8	4736	2776	"
931	1.8	4744	2776	"
932	1.9	4752	2776	"
933	1.6	4760	2779	"
934	1.6	4767	2781	"
935	24.7	4329	2268	+0.06
936	26.9	4292	2269	"
937	26.3	4293	2277	"
938	35.2	4304	1805	+0.15
939	35.1	4296	1806	"
940	35.3	4288	1804	"
941	22.6	4306	1780	"
942	22.7	4301	1778	"
A. 943	22.7	4296	1776	+0.15
944	8.1	4320	1775	"
945	7.8	4325	1779	"
946	7.7	4331	1784	"
947	8.2	4315	1770	"
948	8.4	4310	1765	"
949	8.2	4305	1762	"
950	8.5	4277	1725	"
951	8.7	4271	1723	"
952	29.3	6154	1057	+0.21
953	29.3	6149	1063	"
954	29.8	6144	1070	"
955	30.4	6133	1075	"

Area F heights (D.E.Smith,1965) included in Area A data:

F. 739	16.8	6273	0998	+0.03
740	16.5	6279	0995	"
741	16.3	6284	0993	"
742	16.4	6289	0992	"
743	18.9	6292	0981	"
744	18.8	6285	0982	"
745	18.5	6277	0985	"
746	18.0	6273	0990	"
747	18.3	6265	0992	"

<u>AREA B</u>

B. 1	35.0	2723	2017	0.00
2	34.1	2718	2016	"
3	33.5	2712	2014	"
4	33.3	2705	2011	"
5	33.3	2698	2009	"
6	35.8	2737	2019	"
7	35.1	2744	2020	"
8	34.2	2750	2022	"
9	32.1	2772	2028	"
10	31.4	2776	2028	"
11	30.8	2752	2029	"
12	31.4	2746	2027	"
13	32.5	2735	2024	"
14	21.9	2731	2050	"
15	22.1	2721	2046	"
16	22.2	2716	2044	"
17	21.7	2711	2042	"
18	21.4	2736	2052	"
19	21.4	2743	2054	"
20	21.5	2750	2057	"
21	21.6	2758	2058	"
22	21.4	2766	2060	"

B.	23	21.4	2775	2063	0.00
	24	21.2	2783	2066	"
	25	21.2	2790	2068	"
	26	21.3	2798	2071	"
	27	21.6	2805	2074	"
	28	20.7	2823	2083	"
	29	20.8	2830	2086	"
	30	27.1	2873	2087	"
	31	26.3	2865	2083	"
	32	26.5	2858	2079	"
	33	26.7	2850	2075	"
	34	26.9	2844	2071	"
	35	27.5	2838	2067	"
	36	27.6	2832	2064	"
	37	26.6	2831	2065	"
	38	27.2	2825	2060	"
	39	26.9	2818	2057	"
	40	27.6	2808	2054	"
	41	28.3	2801	2050	"
	42	28.9	2794	2045	"
	43	28.2	2793	2047	"
	44	21.6	2893	2120	-0.04
	45	21.4	2898	2124	"
	46	21.0	2903	2128	"
	47	20.6	2910	2131	"
	48	21.6	2884	2119	"
	49	3.8	2800	2092	"
	50	3.9	2797	2092	"
	51	3.8	2794	2091	"
	52	3.8	2792	2091	"
	53	4.0	2789	2090	"
	54	3.9	2786	2089	"
	55	4.4	2786	2088	"
	56	18.0	2984	2164	+0.01
	57	17.1	2982	2165	"
	58	17.4	2986	2165	"
	59	20.2	3002	2176	"
	60	20.0	3006	2178	"
	61	20.8	3010	2181	"
	62	19.1	2965	2148	"
	63	18.9	2938	2136	"
	64	19.0	2935	2135	"
	65	20.0	2920	2140	"
	66	20.2	2912	2138	"
	67	20.5	2910	2131	"
	68	20.8	2907	2129	"
	69	21.0	2900	2127	"
	70	21.2	2895	2123	"
	71	20.6	2889	2132	"
	72	20.2	2893	2134	"
	73	20.1	2898	2136	"
B.	74	20.1	2901	2138	+0.01
	75	20.0	2905	2140	"
	76	9.1	2969	2175	-0.03
	77	9.1	2965	2174	"
	78	9.1	2960	2173	"
	79	9.2	2956	2172	"
	80	8.8	2953	2171	"
	81	9.2	2972	2176	"
	82	8.9	2978	2180	"
	83	9.4	2986	2183	"
	84	3.0	2947	2174	"
	85	3.0	2950	2175	"
	86	3.0	2953	2176	"
	87	3.2	2961	2180	"
	88	31.1	2748	2028	0.00
	89	30.6	2756	2031	"
	90	29.9	2763	2032	"
	91	29.0	2768	2034	"
	92	28.5	2777	2037	"
	93	27.9	2782	2038	"
	94	28.0	2788	2041	"
	95	10.6	1245	1837	-0.15
	96	10.4	1249	1834	"
	97	10.4	1252	1831	"
	98	10.4	1256	1827	"
	99	10.4	1260	1823	"
	100	10.2	1263	1819	"
	101	10.4	1265	1814	"
	102	10.5	1267	1810	"
	103	10.4	1270	1805	"
	104	10.2	1273	1800	"
	105	10.5	1275	1796	"
	106	10.2	1279	1794	"
	107	11.1	1273	1792	"
	108	11.2	1270	1795	"
	109	11.2	1267	1799	"
	110	11.3	1264	1803	"
	111	11.2	1261	1807	"
	112	11.0	1259	1811	"
	113	10.1	1282	1790	"
	114	10.3	1287	1786	"
	115	10.3	1292	1782	"
	116	10.5	1298	1780	"
	117	10.3	1287	1808	"
	118	10.3	1351	1735	+0.10
	119	10.1	1357	1734	"
	120	10.2	1362	1730	"
	121	10.1	1366	1726	"
	122	10.0	1370	1722	"
	123	9.9	1374	1716	"

B.	124	10.2	1377	1711	+0.10
	125	10.2	1378	1707	"
	126	10.0	1380	1703	"
	127	10.2	1382	1698	"
	128	10.5	1387	1691	"
	129	10.5	1392	1689	"
	130	10.3	1396	1685	"
	131	9.9	1404	1680	"
	132	10.0	1407	1676	"
	133	10.1	1410	1673	"
	134	10.2	1412	1669	"
	135	10.2	1416	1666	"
	136	10.1	1419	1663	"
	137	10.0	1423	1661	"
	138	16.4	1405	1621	"
	139	16.0	1400	1623	"
	140	16.2	1396	1624	"
	141	16.2	1391	1626	"
	142	16.4	1387	1628	"
	143	16.1	1383	1630	"
	144	16.0	1378	1633	"
	145	15.9	1376	1639	"
	146	15.9	1365	1644	"
	147	16.5	1359	1639	"
	148	17.0	1354	1641	"
	149	17.2	1348	1642	"
	150	15.3	1374	1649	"
	151	10.1	1428	1655	"
	152	10.1	1432	1652	"
	153	10.1	1436	1650	"
	154	10.2	1440	1648	"
	155	10.3	1446	1646	"
	156	10.4	1451	1645	"
	157	10.4	1456	1645	"
	158	10.4	1455	1649	"
	159	14.2	1220	1821	+0.02
	160	13.7	1216	1827	"
	161	13.9	1213	1835	"
	162	13.9	1209	1842	"
	163	13.7	1206	1848	"
	164	14.1	1204	1853	"
	165	14.1	1226	1815	"
	166	14.2	122	1815	"
	167	14.0	1228	1808	"
	168	13.9	1234	1801	"
	169	10.7	1246	1697	"
	170	10.3	1251	1697	"
	171	11.0	1256	1697	"
	172	11.0	1261	1697	"
	173	10.9	1266	1697	"
	174	10.5	1270	1698	"
B.	175	10.7	1274	1700	+0.02
	176	11.1	1278	1702	"
	177	10.8	1279	1707	"
	178	10.5	1280	1711	"
	179	17.7	1242	1676	-0.01
	180	17.5	1248	1678	"
	181	18.3	1263	1672	"
	182	17.2	1278	1666	"
	183	16.9	1286	1664	"
	184	17.0	1293	1662	"
	185	16.8	1297	1661	"
	186	17.0	1302	1660	"
	187	16.9	1307	1659	"
	188	17.2	1312	1658	"
	189	10.1	1464	1700	+0.08
	190	9.9	1468	1697	"
	191	10.0	1472	1694	"
	192	10.0	1475	1691	"
	193	9.9	1479	1688	"
	194	9.9	1483	1685	"
	195	9.8	1487	1682	"
	196	9.8	1491	1679	"
	197	9.6	1494	1676	"
	198	9.8	1498	1673	"
	199	10.0	1501	1669	"
	200	10.0	1506	1667	"
	201	10.0	1510	1665	"
	202	9.6	1516	1663	"
	203	9.7	1523	1659	"
	204	10.0	1529	1654	"
	205	10.0	1536	1646	"
	206	10.0	1545	1640	"
	207	9.8	1557	1633	"
	208	10.3	1558	1625	"
	209	10.3	1574	1636	"
	210	10.3	1579	1630	"
	211	10.2	1582	1624	"
	212	10.6	1586	1616	"
	213	11.6	1590	1608	"
	214	10.6	1599	1636	"
	215	10.5	1603	1639	"
	216	10.5	1607	1642	"
	217	10.4	1612	1645	"
	218	10.4	1616	1648	"
	219	10.2	1622	1649	"
	220	9.9	1615	1651	"
	221	9.4	1614	1655	"
	222	9.6	1612	1658	"
	223	9.7	1610	1662	"
	224	9.5	1608	1666	"
	225	9.5	1626	1655	"

B.	226	9.4	1630	1658	+0.08
	227	9.6	1635	1661	"
	228	9.5	1641	1661	"
	229	9.8	1646	1663	"
	230	4.2	1312	1861	-0.09
	231	4.4	1306	1866	"
	232	3.9	1304	1861	"
	233	4.0	1300	1863	"
	234	4.1	1296	1866	"
	235	4.2	1292	1870	"
	236	4.5	1294	1873	"
	237	3.4	1265	1886	"
	238	3.5	1262	1890	"
	239	3.8	1259	1894	"
	240	4.0	1256	1898	"
	241	4.1	1252	1901	"
	242	4.8	1228	1916	-0.01
	243	4.7	1233	1914	"
	244	4.6	1237	1911	"
	245	4.4	1241	1908	"
	246	4.3	1244	1905	"
	247	4.1	1248	1903	"
	248	3.8	1263	1901	"
	249	3.9	1258	1910	"
	250	4.0	1252	1918	"
	251	4.5	1238	1917	"
	252	9.9	1193	1873	-0.02
	253	10.0	1188	1872	"
	254	9.7	1183	1871	"
	255	9.6	1178	1873	"
	256	9.8	1174	1876	"
	257	10.0	1170	1880	"
	258	10.0	1174	1883	"
	259	4.6	1158	1908	"
	260	4.6	1162	1912	"
	261	4.5	1167	1913	"
	262	4.6	1155	1904	"
	263	4.6	1152	1900	"
	264	5.0	1148	1897	"
	265	4.6	1144	1900	"
	266	4.9	1141	1904	"
	267	4.8	1137	1908	"
	268	4.8	1133	1910	"
	269	5.1	1128	1912	"
	270	5.5	1119	1914	"
	271	5.5	1117	1913	"
	272	5.4	1094	1915	"
	273	5.1	1101	1914	"
	274	5.0	1107	1912	"
	275	5.0	1113	1912	"
	276	4.5	1119	1923	"
B.	277	4.6	1109	1922	-0.02
	278	10.3	1079	1912	"
	279	10.2	1073	1911	"
	280	11.1	1067	1905	"
	281	10.7	1062	1905	"
	282	10.6	1049	1907	"
	283	10.6	1042	1909	"
	284	10.5	1037	1910	"
	285	10.7	1032	1910	"
	286	10.8	1028	1911	"
	287	10.9	1023	1912	"
	288	10.0	1613	1906	"
	289	9.8	1615	1902	"
	290	9.9	1619	1903	"
	291	10.0	1623	1904	"
	292	10.2	1627	1905	"
	293	10.1	1624	1883	"
	294	-0.7	2309	1855	0.00
	295	-0.7	2311	1855	"
	296	-0.7	2313	1855	"
	297	-0.7	2315	1855	"
	298	-0.6	2318	1856	"
	299	-0.5	2306	1853	"
	300	-0.5	2303	1853	"
	301	-0.4	2300	1853	"
	302	10.0	2482	1852	"
	303	9.8	2485	1856	"
	304	9.8	2488	1860	"
	305	9.2	2491	1864	"
	306	9.1	2495	1867	"
	307	9.2	2500	1871	"
	308	9.2	2504	1874	"
	309	9.3	2508	1876	"
	310	10.2	2482	1850	"
	311	10.1	2483	1848	"
	312	9.8	2483	1845	"
	313	9.9	2480	1843	"
	314	10.7	1673	1916	-0.06
	315	10.4	1676	1913	"
	316	10.4	1680	1910	"
	317	10.3	1683	1907	"
	318	10.2	1686	1904	"
	319	11.0	1670	1919	"
	320	11.3	1667	1923	"
	321	12.0	1665	1925	"
	322	12.6	1662	1927	"
	323	10.6	1664	1917	"
	324	10.3	1656	1915	"
	325	10.1	1649	1912	"
	326	9.9	1643	1908	"
	327	10.1	1635	1905	"

B.	328	10.9	1634	1910	-0.06	B.	379	26.7	1698	1998	-0.01
	329	10.9	1651	1918	"		380	26.9	1695	1995	"
	330	10.6	1679	1921	"		381	26.4	1693	1991	"
	331	10.5	1684	1926	"		382	27.1	1690	1988	"
	332	10.5	1689	1930	"		383	26.9	1688	1983	"
	333	10.3	1714	1943	"		384	3.8	1798	1823	+0.22
	334	10.2	1710	1939	"		385	3.8	1792	1821	"
	335	10.3	1705	1934	"		386	3.7	1786	1818	"
	336	10.4	1700	1930	"		387	3.9	1780	1815	"
	337	10.6	1705	1923	"		388	3.8	1774	1812	"
	338	10.5	1718	1931	"		389	3.6	1438	1845	-0.01
	339	10.2	1720	1947	"		390	3.5	1447	1843	"
	340	10.2	1727	1950	"		391	3.4	1455	1841	"
	341	10.1	1733	1950	"		392	4.1	1462	1826	"
	342	10.5	1741	1955	"		393	4.0	1469	1825	"
	343	10.2	1746	1959	"		394	3.8	1477	1824	"
	344	10.4	1753	1962	"		395	3.7	1484	1824	"
	345	9.9	1762	1957	"		396	3.5	1491	1821	"
	346	10.2	1763	1966	"		397	3.4	1499	1820	"
	347	10.4	1764	1978	"		398	3.2	1505	1820	"
	348	9.9	1763	1994	"		399	3.0	1511	1820	"
	349	10.1	1760	1988	"		400	3.1	1517	1822	"
	350	9.9	1756	1982	"		401	3.1	1522	1827	"
	351	9.9	1751	1978	"		402	3.1	1528	1833	"
	352	4.0	1551	1838	-0.01		403	3.2	1534	1837	"
	353	3.9	1559	1838	"		404	3.1	1541	1838	"
	354	3.9	1566	1837	"		405	10.5	1175	1984	+0.25
	355	4.0	1573	1835	"		406	10.4	1168	1985	"
	356	4.5	1580	1832	"		407	10.5	1162	1987	"
	357	11.5	1197	1981	+0.25		408	16.7	1187	1768	0.00
	358	11.6	1190	1982	"		409	16.5	1193	1763	"
	359	11.2	1182	1983	"		410	16.8	1197	1755	"
	360	14.5	1712	1993	-0.04		411	15.8	1021	1890	"
	361	15.2	1708	1989	"		412	16.1	1027	1891	"
	362	15.7	1704	1985	"		413	2.6	1833	1922	+0.10
	363	16.0	1700	1981	"		414	2.0	1830	1934	"
	364	11.5	1725	1989	"		415	1.7	1848	1932	"
	365	11.1	1729	1995	"		416	1.7	1858	1925	"
	366	11.9	1724	1987	"		417	1.9	1835	1915	"
	367	11.8	1722	1983	"		418	1.6	1835	1908	"
	368	11.3	1721	1977	"		419	1.6	1838	1901	"
	369	3.3	1560	1847	-0.01		420	1.7	1841	1895	"
	370	3.3	1568	1846	"		421	2.3	1848	1900	+0.10
	371	11.0	1716	1970	-0.04		422	2.4	1852	1896	"
	372	11.2	1709	1966	"		423	2.5	1856	1893	"
	373	11.4	1699	1965	"		424	2.9	1841	1841	+0.05
	374	11.6	1693	1959	"		425	3.0	1834	1841	"
	375	11.8	1687	1955	"		426	3.8	1828	1845	"
	376	11.9	1680	1949	"		427	3.2	1827	1839	"
	377	11.8	1675	1945	"		428	3.7	1821	1847	"
	378	11.9	1671	1941	"		429	3.7	1813	1847	"

B.	430	2.8	1848	1838	+0.05	B.	481	26.5	1472	1920	+0.32
	431	2.6	1856	1835	"		482	25.9	1476	1919	"
	432	2.7	1864	1833	"		483	25.6	1481	1917	"
	433	2.5	1871	1832	"		484	24.9	1485	1917	"
	434	2.4	1880	1831	"		485	24.9	1489	1916	"
	435	2.7	1888	1830	"		486	24.6	1493	1915	"
	436	4.3	1901	1829	"		487	28.0	1452	1917	"
	437	4.5	1905	1834	"		488	28.3	1445	1915	"
	438	4.0	1909	1839	"		489	27.6	1440	1916	"
	439	3.6	1912	1845	"		490	27.2	1435	1916	"
	440	3.6	1915	1850	"		491	26.9	1430	1917	"
	441	4.4	1590	1859	+0.06		492	28.2	1425	1918	"
	442	4.6	1585	1864	"		493	28.3	1420	1919	"
	443	4.6	1580	1869	"		494	28.5	1415	1920	"
	444	4.7	1576	1875	"		495	30.8	1440	1928	"
	445	6.2	1571	1869	"		496	31.7	1435	1929	"
	446	5.5	1574	1866	"		497	32.2	1430	1929	"
	447	4.0	1597	1854	"		498	32.6	1426	1930	"
	448	4.1	1604	1851	"		499	28.5	1410	1922	"
	449	4.0	1611	1848	"		500	28.9	1405	1922	"
	450	4.0	1619	1845	"		501	28.7	1400	1921	"
	451	4.0	1625	1844	"		502	29.1	1395	1920	"
	452	3.8	1629	1844	"		503	29.1	1354	1918	"
	453	3.7	1633	1844	"		504	29.2	1350	1918	"
	454	3.4	1639	1847	"		505	29.1	1345	1918	"
	455	3.2	1645	1850	"		506	28.8	1340	1918	"
	456	3.2	1651	1853	"		507	28.9	1335	1918	"
	457	3,2	1658	1857	"		508	29.3	1331	1919	"
	458	3.2	1665	1860	"		509	29.6	1326	1921	"
	459	3.2	1673	1862	"		510	37.5	1336	1934	"
	460	3.2	1680	1864	"		511	35.8	1338	1939	"
	461	10.3	1480	1870	+0.05		512	35.7	1331	1941	"
	462	10.3	1472	1868	"		513	22.2	1502	1556	+0.01
	463	10.3	1464	1868	"		514	21.6	1504	1556	"
	464	10.4	1456	1868	"		515	22.6	1497	1555	"
	465	10.2	1448	1868	"		516	29.6	1513	1536	"
	466	5.3	1510	1871	"		517	29.3	1517	1537	"
	467	4.9	1504	1867	"		518	30.2	1509	1535	"
	468	4.9	1504	1862	"		519	31.0	1504	1534	"
	469	5.6	1517	1873	"		520	31.9	1499	1533	"
	470	5.0	1526	1873	"		521	32.7	1493	1532	"
	471	5.0	1534	1873	"		522	32.2	1506	1532	"
	472	5.1	1541	1868	"		523	16.7	1493	1575	- 0.03
	473	6.0	1529	1866	"		524	16.6	1496	1578	"
	474	5.9	1519	1864	"		525	16.5	1501	1579	"
	475	14.0	1474	1885	+0.32		526	16.3	1505	1579	"
	476	14.0	1467	1885	"		527	16.5	1509	1577	"
	477	14.1	1460	1885	"		528	16.9	1513	1574	"
	478	13.8	1453	1885	"		529	15.7	1533	1562	"
	479	13.7	1445	1885	"		530	16.4	1536	1562	"
	480	26.7	1467	1921	"		531	16.6	1539	1561	"

B.	532	18.4	1653	1583	+0.06
	533	19.0	1651	1578	"
	534	19.8	1650	1574	"
	535	20.8	1649	1570	"
	536	28.4	1651	1556	"
	537	27.5	1654	1558	"
	538	26.7	1658	1561	"
	539	26.3	1662	1564	"
	540	25.8	1666	1565	"
	541	24.9	1671	1569	"
	542	24.7	1675	1572	"
	543	24.4	1678	1575	"
	544	28.7	1672	1564	"
	545	29.1	1668	1562	"
	546	29.1	1676	1564	"
	547	29.4	1680	1564	"
	548	27.4	1679	1568	"
	549	27.2	1684	1568	"
	550	27.3	1689	1566	"
	551	27.3	1693	1565	"
	552	26.9	1697	1564	"
	553	26.9	1702	1564	"
	554	26.8	1706	1565	"
	555	26.7	1711	1566	"
	556	27.0	1715	1567	"
	557	27,0	1719	1568	"
	558	27.8	1724	1570	"
	559	27.0	1729	1571	"
	560	27.4	1733	1573	"
	561	28.3	1738	1574	"
	562	27.5	1737	1576	"
	563	13.4	1696	1594	"
	564	13.6	1701	1595	"
	565	13.9	1705	1594	"
	566	13.8	1691	1593	"
	567	14.0	1686	1593	"
	568	14.1	1681	1592	"
	569	14.1	1676	1591	"
	570	14.2	1671	1591	"
	571	14.7	1667	1590	"
	572	15.5	1662	1589	"
	573	16.1	1658	1587	"
	574	18.8	1615	1558	-0.01
	575	19.2	1619	1555	"
	576	19.8	1622	1552	"
	577	20.3	1624	1548	"
	578	20.6	1628	1546	"
	579	17.8	1610	1560	"
	580	17.8	1605	1561	"
	581	17.3	1600	1560	"
	582	16.7	1596	1558	"
B.	583	16.3	1592	1556	-0.01
	584	16.2	1587	1555	"
	585	15.7	1583	1553	"
	586	16.0	1578	1553	"
	587	16.1	1573	1553	"
	588	15.1	1569	1556	"
	589	13.6	1754	1602	-0.05
	590	12.9	1749	1601	"
	591	13.2	1745	1600	"
	592	13.3	1740	1600	"
	593	13.5	1731	1600	"
	594	13.2	1727	1599	"
	595	12.9	1722	1598	"
	596	13.7	1756	1602	"
	597	14.1	1760	1604	"
	598	14.4	1765	1605	"
	599	14.8	1769	1607	"
	600	14.8	1773	1609	"
	601	14.8	1777	1610	"
	602	14.6	1781	1614	"
	603	14.3	1785	1618	"
	604	14.5	1789	1621	"
	605	12.9	1894	1707	-0.12
	606	13.2	1891	1704	"
	607	13.2	1888	1701	"
	608	13.3	1884	1698	"
	609	13.4	1880	1696	"
	610	13.5	1877	1693	"
	611	13.8	1873	1689	"
	612	14.0	1869	1686	"
	613	14.6	1866	1679	"
	614	14.5	1857	1676	"
	615	14.2	1855	1672	"
	616	13.2	1899	1707	"
	617	13.0	1904	1708	"
	618	12.9	1907	1711	"
	619	13.3	1910	1713	"
	620	13.2	1913	1716	"
	621	13.1	1917	1719	"
	622	13.1	1920	1721	"
	623	13.0	1925	1725	"
	624	13.3	1929	1728	"
	625	13.0	1932	1730	"
	626	12.6	1936	1733	"
	627	12.7	1940	1736	"
	628	12.1	1944	1740	"
	629	12.2	1947	1743	"
	630	12.7	1951	1745	"
	631	12.5	1954	1749	"
	632	12.4	1958	1753	"
	633	12.2	1962	1756	"

B.	634	12.4	1966	1760	-0.12	B.	685	9.3	1873	1778	-0.13
	635	12.9	1970	1762	"		686	9.4	1878	1779	"
	636	25.9	1982	1726	"		687	9.8	1862	1773	"
	637	25.6	1985	1729	"		688	9.9	1857	1771	"
	638	25.5	1989	1731	"		689	10.0	1852	1769	"
	639	25.6	1993	1734	"		690	9.8	1847	1766	"
	640	25.5	1996	1737	"		691	9.8	1843	1765	"
	641	25.9	1979	1723	"		692	9.8	1839	1760	"
	642	25.2	1976	1720	"		693	9.8	1834	1758	"
	643	12.9	1996	1778	+0.08		694	9.5	1829	1756	"
	644	12.5	1993	1776	"		695	25.4	3573	2449	+0.01
	645	13.0	1989	1773	"		696	23.8	3568	2449	"
	646	13.1	1984	1771	"		697	22.3	3562	2449	"
	647	12.3	1999	1881	"		698	22.3	3557	2447	"
	648	12.7	2003	1785	"		699	25.9	3576	2449	"
	649	12.7	2006	1788	"		700	26.9	3581	2450	"
	650	13.1	2010	1790	"		701	27.2	3585	2450	"
	651	12.6	2023	1797	"		702	36.1	3434	2377	+0.06
	652	12.2	2016	1794	"		703	36.1	3439	2378	"
	653	12.6	2013	1792	"		704	36.1	3443	2380	"
	654	12.3	2028	1798	"		705	35.7	3447	2382	"
	655	12.9	2035	1800	"		706	36.1	3430	2376	"
	656	12.4	2039	1802	"		707	35.8	3427	2376	"
	657	12.0	2037	1806	"		708	35.8	3423	2376	"
	658	11.2	2044	1809	"		709	3.4	2449	1865	+0.10
	659	24.6	2060	1800	"		710	3.4	2455	1868	"
	660	25.3	2060	1797	"		711	3.2	2461	1872	"
	661	25.4	2058	1795	"		712	3.4	2466	1874	"
	662	25.4	2032	1768	"		713	3.2	2473	1876	"
	663	25.5	2028	1766	"		714	3.4	2480	1878	"
	664	25.1	2025	1762	"		715	3.3	2486	1882	"
	665	25.2	2017	1751	"		716	3.3	2493	1882	"
	666	25.7	2013	1749	"		717	3.5	2500	1885	"
	667	26.2	1998	1741	"		718	3.2	2507	1888	"
	668	25.9	2001	1745	"		719	3.4	2513	1891	"
	669	25.9	2005	1743	"		720	3.4	2519	1895	"
	670	25.8	2019	1747	"		721	3.3	2525	1899	"
	671	9.5	1977	1815	-0.03		722	14.3	1366	1893	+0.04
	672	9.7	1981	1817	"		723	14.7	1389	1894	"
	673	9.6	1985	1820	"		724	16.8	1337	1904	"
	674	8.9	1985	1828	"		725	16.4	1332	1904	"
	675	8.9	1980	1828	"		726	16.3	1327	1905	"
	676	8.9	1975	1828	"		727	16.1	1322	1907	"
	677	9.0	1971	1828	"		728	15.8	1313	1909	"
	678	9.7	1972	1814	"		729	4.2	1333	1856	"
	679	9.7	1967	1813	"		730	4.3	1341	1856	"
	680	9.8	1962	1811	"		731	4.4	1348	1855	"
	681	9.7	1958	1808	"		732	4.0	1356	1855	"
	682	9.6	1956	1804	"		733	3.8	1364	1857	"
	683	9.8	1863	1778	-0.13		734	3.7	1372	1857	"
	684	9.7	1868	1778	"		735	4.4	1371	1862	"

B.	736	4.5	1363	1860	+0.04
	737	4.5	1355	1860	"
	738	4.7	1347	1860	"
	739	4.5	1339	1861	"
	740	4.7	1332	1864	"
	741	9.4	1911	1788	+0.22
	742	9.5	1919	1787	"
	743	9.3	1927	1785	"
	744	3.0	1898	1798	"
	745	2.9	1890	1801	"
	746	2.8	1882	1802	"
	747	2.9	1874	1803	"
	748	3.0	1866	1805	"
	749	3.0	1861	1810	"
	750	9.1	1813	1811	"
	751	9.2	1806	1810	"
	752	9.1	1798	1809	"
	753	9.2	1791	1808	"
	754	9.2	1783	1807	"
	755	4.1	1696	1787	+0.12
	756	4.4	1689	1790	"
	757	4.3	1682	1794	"
	758	4.3	1676	1799	"
	759	4.6	1670	1803	"
	760	4.5	1665	1810	"
	761	4.1	1660	1815	"
	762	3.2	1685	1838	"
	763	3.2	1688	1834	"
	764	3.2	1690	1830	"
	765	3.0	1693	1827	"
	766	4.1	1677	1811	"
	767	4.1	1684	1806	"
	768	3.9	1690	1801	"
	769	4.1	1455	1828	-0.01
	770	4.2	1448	1829	"
	771	4.2	1440	1831	"
	772	4.3	1433	1832	"
	773	4.3	1425	1833	"
	774	4.5	1418	1833	"

AREA C

C.	1	10.2	0967	1919	-0.02
	2	10.5	0962	1919	"
	3	10.5	0957	1919	"
	4	10.7	0953	1920	"
	5	5.4	0984	1955	-0.03
	6	5.4	0987	1947	"
	7	5.8	0979	1942	"
	8	5.9	0977	1947	"
	9	5.7	0970	1943	"
C.	10	6.0	0968	1947	-0.03
	11	6.0	0964	1951	"
	12	6.3	1443	2233	-0.02
	13	6.4	1448	2236	"
	14	4.2	1536	2239	+0.06
	15	4.2	1542	2238	"
	16	4.2	1549	2235	"
	17	4.3	1557	2231	"
	18	4.3	1564	2226	"
	19	4.2	1570	2220	"
	20	4.3	1574	2213	"
	21	4.3	1576	2206	"
	22	9.8	1797	2094	0.00
	23	5.6	0819	1949	+0.29
	24	5.8	0813	1948	"
	25	5.9	0809	1945	"
	26	6.2	0806	1941	"
	27	6.0	0801	1939	"
	28	5.9	0797	1937	"
	29	6.1	0792	1936	"
	30	5.8	0802	1953	"
	31	5.6	0810	1953	"
	32	10.3	0863	1929	"
	33	10.6	0850	1926	"
	34	10.4	0842	1922	"
	35	11.0	0836	1917	"
	36	10.8	0810	1907	"
	37	10.5	0803	1904	"
	38	10.5	0798	1902	"
	39	10.6	0794	1899	"
	40	10.7	0790	1896	"
	41	10.8	0786	1893	"
	42	10.8	0782	1891	"
	43	10.8	0778	1889	"
	44	10.8	0769	1885	"
	45	10.6	0764	1883	"
	46	10.5	0763	1888	"
	47	11.5	0688	1835	-0.07
	48	10.9	0689	1839	"
	49	10.9	0693	1843	"
	50	11.0	0698	1847	"
	51	10.8	0703	1850	"
	52	10.9	0709	1854	"
	53	21.0	0705	1834	"
	54	20.9	0702	1832	"
	55	21.0	0699	1829	"
	56	31.6	0709	1822	"
	57	31.6	0708	1818	"
	58	31.0	0703	1810	"
	59	32.3	0698	1806	"
	60	31.6	0693	1803	"

C.	61	17.3	0728	1852	-0.07	C.	112	9.6	0531 1816	-0.17
	62	17.6	0734	1853	"		113	9.8	0524 1813	"
	63	15.9	0732	1857	"		114	9.8	0517 1811	"
	64	15.9	0727	1855	"		115	9.9	0510 1807	"
	65	15.3	0735	1860	"		116	10.2	0504 1805	"
	66	16.0	0737	1856	"		117	11.0	0625 1791	"
	67	15.5	0743	1858	"		118	11.2	0636 1796	"
	68	14.8	0767	1873	"		119	11.2	0643 1800	"
	69	14.7	0772	1874	"		120	11.3	0647 1803	"
	70	14.5	0777	1875	"		121	11.1	0668 1823	0.00
	71	14.5	0783	1876	"		122	11.0	0672 1826	"
	72	14.6	0787	1877	"		123	14.4	0892 1902	"
	73	7.0	0739	1887	"		124	14.4	0888 1903	"
	74	6.4	0748	1892	"		125	14.6	0883 1903	"
	75	6.6	0751	1894	"		126	15.0	0878 1903	"
	76	6.2	0754	1898	"		127	15.0	0878 1907	"
	77	6.1	0770	1902	"		128	15.0	0874 1904	"
	78	6.0	0775	1905	"		129	14.9	0946 1890	"
	79	6.7	0783	1911	"		130	14.8	0951 1889	"
	80	6.1	0786	1915	"		131	14.7	0956 1890	"
	81	6.0	0769	1915	"		132	18.1	0860 1884	"
	82	6.6	0762	1908	"		133	18.2	0865 1884	"
	83	5.9	0758	1919	"		134	17.9	0871 1884	"
	84	6.0	0753	1919	"		135	18.3	0877 1884	"
	85	6.1	0749	1920	"		136	17.9	0883 1885	"
	86	7.0	0733	1886	"		137	13.0	0823 1894	+0.29
	87	7.2	0727	1887	"		138	13.2	0818 1893	"
	88	7.3	0721	1888	"		139	22.8	0528 1749	+0.11
	89	7.6	0645	1894	-0.12		140	23.9	0527 1739	"
	90	7.5	0650	1894	"		141	24.5	0523 1733	"
	91	7.4	0656	1893	"		142	25.7	0519 1726	"
	92	7.3	0661	1894	"		143	26.6	0518 1713	"
	93	7.2	0667	1896	"		144	27.6	0514 1710	"
	94	7.1	0672	1899	"		145	31.9	0527 1683	"
	95	7.7	0628	1863	-0.17		146	33.0	0527 1675	"
	96	7.6	0634	1864	"		147	33.8	0532 1668	"
	97	7.5	0637	1869	"		148	34.4	0538 1674	"
	98	7.4	0638	1874	"		149	33.5	0539 1682	"
	99	8.0	0625	1854	"		150	32.8	0540 1689	"
	100	8.1	0618	1852	"		151	32.0	0542 1695	"
	101	8.1	0611	1848	"		152	31.1	0546 1700	"
	102	8.1	0603	1846	"		153	30.9	0550 1706	"
	103	8.3	0596	1843	"		154	28.7	0554 1710	"
	104	8.3	0586	1838	"		155	27.7	0557 1715	"
	105	8.4	0580	1836	"		156	26.6	0562 1720	"
	106	8.5	0573	1833	"		157	24.8	0566 1725	"
	107	8.8	0566	1830	"		158	24.3	0570 1733	"
	108	9.0	0559	1827	"		159	41.9	0673 1758	+0.10
	109	9.2	0552	1824	"		160	42.2	0669 1751	"
	110	8.7	0545	1822	"		161	42.1	0666 1744	"
	111	9.1	0538	1819	"		162	41.8	0666 1736	"

C.	163	42.6	0656	1729	+0.10
	164	42.8	0653	1722	"
	165	43.1	0647	1717	"
	166	43.3	0641	1714	"
	167	33.8	0633	1748	"
	168	33.8	0623	1750	"
	169	33.3	0615	1744	"
	170	33.6	0652	1762	"
	171	33.3	0657	1766	"
	172	33.2	0661	1771	"
	173	31.6	0665	1776	"
	174	32.0	0671	1781	"
	175	31.6	0682	1791	"
	176	31.8	0686	1796	"
	177	42.0	0688	1780	"
	178	42.2	0693	1784	"
	179	42.2	0697	1787	"
	180	31.0	0841	1861	-0.08
	181	30.9	0834	1862	"
	182	31.2	0826	1863	"
	183	31.7	0818	1863	"
	184	31.7	0810	1862	"
	185	41.5	0805	1845	"
	186	40.8	0798	1845	"
	187	40.6	0791	1844	"
	188	40.9	0784	1843	"
	189	41.6	0776	1841	"
	190	41.9	0771	1837	"
	191	5.5	0978	1962	-0.03
	192	4.3	1631	2122	+0.05
	193	4.3	1623	2125	"
	194	4.4	1615	2128	"
	195	9.9	1557	2145	"
	196	18.7	0683	1963	-0.01
	197	18.5	0677	1962	"
	198	11.6	0704	1959	"
	199	11.4	0710	1963	"
	200	10.9	0718	1964	"
	201	11.2	0725	1967	"
	202	11.1	0732	1970	"
	203	11.2	0738	1972	"
	204	17.8	0703	1967	"
	205	17.6	0716	1970	"
	206	9.8	1550	2147	0.00
	207	10.1	1543	2151	"
	208	9.9	1536	2153	"
	209	9.7	1528	2154	"
	210	9.6	1520	2154	"
	211	9.6	1513	2158	"
	212	9.9	1507	2161	"
	213	10.0	1502	2166	"
	214	9.9	1496	2171	"
C.	215	10.3	1455	2183	0.00
	216	10.0	1448	2182	"
	217	10.1	1440	2179	"
	218	9.8	1433	2179	"
	219	9.8	1426	2179	"
	220	38.0	0748	2492	-0.01
	221	37.7	0755	2492	"
	222	37.5	0763	2492	"
	223	37.0	0772	2491	"
	224	36.2	0875	2482	0.00
	225	36.1	0884	2483	"
	226	36.6	0891	2484	"
	227	36.7	0830	2480	"
	228	37.2	0822	2480	"
	229	36.3	0815	2481	"
	230	36.1	0807	2484	"
	231	36.5	0798	2484	"
	232	11.2	1098	2749	-0.07
	233	11.2	1090	2750	"
	234	10.9	1083	2750	"
	235	11.0	1076	2748	"
	236	11.0	1069	2747	"
	237	11.1	1063	2744	"
	238	11.1	1057	2740	"
	239	10.9	1051	2737	"
	240	10.9	1044	2736	"
	241	11.1	1037	2739	"
	242	11.2	1031	2744	"
	243	11.2	1026	2749	"
	244	11.2	1021	2755	"
	245	11.4	1016	2761	"
	246	11.7	1013	2766	"
	247	11.1	1010	2772	"
	248	11.5	1006	2778	"
	249	10.7	1108	2719	"
	250	10.7	1114	2716	"
	251	10.9	1120	2712	"
	252	11.1	1127	2708	"
	253	11.0	1128	2690	"
	254	10.8	1125	2684	"
	255	10.6	1118	2667	"
	256	10.6	1123	2650	"
	257	10.9	1128	2645	"
	258	10.5	1133	2631	"
	259	7.5	1060	2655	"
	260	7.5	1070	2655	"
	261	7.3	1079	2654	"
	262	7.1	1085	2644	"
	263	7.5	1092	2637	"
	264	7.4	1101	2632	"
	265	7.1	1109	2627	"

C.	266	6.7	1113	2621	-0.07	C.	317	3.6	1309	2138	+0.06
	267	6.5	1119	2613	"		318	3.7	1302	2135	"
	268	6.8	1123	2618	"		319	3.8	1295	2133	"
	269	31.4	1132	2947	-0.02		320	4.1	1287	2132	"
	270	31.8	1131	2954	"		321	28.2	1339	2134	"
	271	31.4	1132	2940	"		322	28.1	1335	2134	"
	272	30.9	1132	2934	"		323	6.6	0706	1942	-0.11
	273	30.8	1118	2918	"		324	6.7	0698	1943	"
	274	30.2	1118	2909	"		325	7.0	0691	1943	"
	275	29.9	1118	2903	"		326	6.5	0716	1942	"
	276	30.1	1120	2895	"		327	6.6	0725	1945	"
	277	29.6	1137	2870	"		328	6.9	0732	1948	"
	278	28.9	1138	2863	"		329	6.6	0743	1952	"
	279	28.1	1139	2857	"		330	6.6	0755	1951	"
	280	28.0	1139	2850	"		331	18.4	0787	1996	"
	281	16.0	1079	2970	0.00		332	18.6	0791	1997	"
	282	15.7	1079	2963	"		333	18.9	0796	1998	"
	283	14.9	1076	2957	"		334	19.0	0801	1999	"
	284	14.2	1072	2950	"		335	9.9	1762	2004	-0.06
	285	14.5	1080	2954	"		336	9.6	1759	2011	"
	286	5.3	1171	2417	"		337	9.8	1755	2017	"
	287	5.4	1169	2423	"		338	11.6	1735	2012	-0.04
	288	5.4	1167	2429	"		339	11.6	1731	2019	"
	289	5.5	1171	2437	"		340	15.6	1721	2003	"
	290	5.4	1168	2444	"		341	15.5	1721	2007	"
	291	5.4	1166	2450	"		342	15.4	1720	2010	"
	292	5.5	1163	2459	"		343	11.2	1734	2000	"
	293	5.7	1162	2465	"		344	11.5	1736	2007	"
	294	5.8	1161	2473	"		345	26.6	1700	2007	-0.01
	295	5.8	1160	2481	"		346	26.9	1700	2012	"
	296	4.3	1157	2310	"		347	26.7	1699	2018	"
	297	4.1	1159	2303	"		348	26.6	1696	2022	"
	298	3.7	1158	2296	"		349	27.1	1688	2032	"
	299	4.1	1155	2285	"		350	12.2	1707	2040	"
	300	4.1	1153	2276	"		351	12.2	1711	2035	"
	301	4.0	1155	2269	"		352	11.7	1717	2032	"
	302	4.4	1173	2308	"		353	9.9	1725	2044	"
	303	4.6	1185	2307	"		354	9.8	1717	2047	"
	304	4.6	1180	2300	"		355	9.7	1711	2051	"
	305	4.5	1177	2294	"		356	9.8	1706	2056	"
	306	4.2	1173	2287	"		357	9.7	1732	2041	"
	307	30.8	1203	2569	+0.03		358	10.0	1738	2036	"
	308	31.1	1201	2574	"		359	9.9	1743	2031	"
	309	32.0	1210	2562	"		360	9.9	1747	2027	"
	310	30.9	1209	2555	"		361	2.5	1740	2051	"
	311	31.0	1212	2549	"		362	2.6	1747	2046	"
	312	31.4	1213	2542	"		363	2.7	1752	2041	"
	313	3.2	1337	2149	+0.06		364	2.9	1759	2036	"
	314	3.2	1330	2147	"		365	4.0	1758	2032	"
	315	3.1	1323	2144	"		366	4.2	1761	2028	"
	316	3.2	1316	2141	"		367	4.2	1765	2025	"

C.	368	4.2	1769	2022	-0.01
	369	4.1	1773	2018	"
	370	10.1	1307	2199	-0.02
	371	10.2	1299	2197	"
	372	10.3	1292	2195	"
	373	10.2	1324	2226	"
	374	10.4	1331	2231	"
	375	9.9	1338	2235	"
	376	10.0	1345	2239	"
	377	10.1	1352	2242	"
	378	10.1	1360	2244	"
	379	10.1	1368	2243	"
	380	10.0	1384	2243	"
	381	9.9	1398	2243	"
	382	9.9	1405	2241	"
	383	10.1	1412	2240	"
	384	10.1	1421	2241	"
	385	10.2	1436	2238	"
	386	6.5	1789	2075	0.00
	387	6.4	1796	2071	"
	388	4.8	1764	2095	"
	389	4.7	1759	2100	"
	390	4.5	1754	2107	"
	391	4.5	1750	2113	"
	392	4.5	1745	2119	"
	393	4.7	1739	2124	"
	394	4.4	1733	2128	"

AREA D

D.	1	9.9	2034	2223	-0.03
	2	10.2	2048	2251	"
	3	10.5	2054	2265	"
	4	9.8	2768	2864	-0.09
	5	10.0	2767	2872	"
	6	9.8	2766	2879	"
	7	9.8	2765	2887	"
	8	9.8	2767	2894	"
	9	9.9	2767	2900	"
	10	10.2	2766	2908	"
	11	10.7	2764	2915	"
	12	10.1	2750	2947	"
	13	9.9	2734	2951	"
	14	10.1	2730	2958	"
	15	10.1	2726	2964	"
	16	10.0	2722	2970	"
	17	10.1	2718	2976	"
	18	10.1	2714	2982	"
	19	10.1	2712	2987	"
	20	10.2	2706	2983	"
	21	10.1	2700	2978	"
D.	22	10.2	2695	2973	-0.09
	23	10.2	2690	2969	"
	24	10.3	2657	2946	"
	25	10.2	2650	2943	"
	26	10.5	2643	2941	"
	27	10.4	2636	2939	"
	28	10.0	2629	2936	"
	29	10.1	2622	2934	"
	30	10.1	2615	2933	"
	31	10.1	2607	2931	"
	32	10.4	2600	2927	"
	33	10.4	2587	2910	+0.16
	34	10.4	2578	2902	"
	35	12.1	2573	2916	"
	36	12.2	2568	2913	"
	37	12.2	2563	2910	"
	38	11.8	2559	2908	"
	39	12.2	2554	2906	"
	40	10.1	2553	2879	"
	41	10.4	2530	2872	"
	42	10.8	2525	2878	"
	43	10.4	2533	2866	"
	44	10.3	2537	2861	"
	45	10.2	2541	2854	"
	46	10.1	2545	2849	"
	47	9.9	2549	2842	"
	48	10.1	2552	2837	"
	49	10.2	2556	2831	"
	50	10.3	2559	2825	"
	51	10.2	2564	2818	"
	52	10.3	2567	2812	"
	53	10.2	2575	2811	"
	54	10.1	2585	2812	"
	55	10.0	2592	2808	"
	56	10.2	2565	2811	"
	57	10.2	2558	2811	"
	58	10.4	2552	2809	"
	59	10.3	2547	2804	"
	60	10.4	2541	2800	"
	61	10.4	2530	2793	"
	62	10.4	2523	2789	"
	63	10.4	2517	2787	"
	64	10.5	2510	2784	"
	65	10.5	2503	2782	"
	66	10.2	2498	2781	"
	67	10.1	2494	2775	"
	68	10.3	2489	2769	"
	69	10.5	2485	2763	"
	70	10.4	2481	2757	"
	71	10.6	2479	2751	"
	72	10.6	2478	2744	"

D.	73	10.5	2477	2737	+0.16	D.	124	11.2	1973	2055	-0.03
	74	10.2	2476	2731	"		125	10.1	2000	2046	"
	75	10.1	2475	2724	"		126	10.2	2009	2049	"
	76	10.0	2471	2718	"		127	10.1	2017	2048	"
	77	11.2	2474	2686	"		128	10.2	2024	2047	"
	78	11.1	2477	2678	"		129	10.5	2033	2056	"
	79	11.1	2482	2671	"		130	10.9	2041	2054	"
	80	10.5	2501	2659	"		131	11.1	2048	2052	"
	81	10.5	2511	2656	"		132	11.2	2056	2048	"
	82	10.5	2521	2656	"		133	11.0	2062	2045	"
	83	10.7	2531	2657	"		134	9.6	2049	2036	"
	84	10.3	2537	2654	"		135	9.7	2041	2036	"
	85	10.1	2543	2650	"		136	9.7	2058	2035	"
	86	10.1	2551	2650	"		137	9.8	2065	2035	"
	87	10.1	2560	2652	"		138	9.8	2091	2032	"
	88	9.9	2568	2650	"		139	9.7	2099	2031	"
	89	9.9	2576	2652	"		140	9.7	2108	2031	"
	90	9.9	2583	2656	"		141	9.6	2114	2031	"
	91	9.9	2589	2662	"		142	9.4	2123	2031	"
	92	10.0	2592	2669	"		143	9.4	2131	2031	"
	93	9.9	2589	2676	"		144	9.6	2138	2030	"
	94	9.9	2586	2682	"		145	9.2	2145	2030	"
	95	10.0	2582	2688	"		146	9.4	2152	2033	"
	96	10.2	2578	2694	"		147	9.3	2159	2033	"
	97	9.9	2588	2714	"		148	9.6	2166	2036	"
	98	10.0	2593	2719	"		149	9.4	2172	2038	"
	99	9.9	2598	2725	"		150	9.5	2178	2038	"
	100	9.8	2604	2730	"		151	11.8	2422	2346	+0.02
	101	9.9	2609	2735	"		152	11.8	2423	2344	"
	102	9.9	2615	2739	"		153	11.8	2424	2342	"
	103	5.4	1842	2035	-0.03		154	11.4	2448	2333	"
	104	5.4	1850	2033	"		155	11,4	2455	2334	"
	105	5.5	1857	2029	"		156	11.2	2463	2335	"
	106	2.1	1851	2013	"		157	11.0	2470	2336	"
	107	3.3	1854	2006	"		158	11.2	2477	2337	"
	108	3.3	1861	2003	"		159	11.1	2484	2340	"
	109	3.5	1870	2002	"		160	10.9	2491	2344	"
	110	3.5	1877	2002	"		161	10.8	2496	2348	"
	111	5.5	1864	2027	"		162	10.9	2500	2353	"
	112	5.4	1872	2026	"		163	10.7	2503	2356	"
	113	9.7	1940	2044	"		164	10.2	2509	2360	"
	114	9.8	1933	2049	"		165	10.2	2516	2366	"
	115	9.4	1926	2052	"		166	10.1	2521	2372	"
	116	9.5	1926	2048	"		167	9.9	2526	2379	"
	117	9.1	1933	2044	"		168	10.0	2530	2385	"
	118	9.1	1940	2039	"		169	10.1	2537	2390	"
	119	8.9	1947	2040	"		170	10.1	2544	2395	"
	120	10.9	1962	2055	"		171	9.9	2551	2398	"
	121	10.9	1954	2056	"		172	9.5	2557	2403	"
	122	11.1	1946	2056	"		173	9.4	2564	2408	"
	123	11.2	1939	2057	"		174	9.6	2571	2412	"

D.	175	10.0	2576	2406	+0.02	D.	226	9.6	2391	2115	+0.02
	176	9.8	2579	2398	"		227	9.4	2383	2113	"
	177	9.7	2581	2391	"		228	9.5	2376	2111	"
	178	9.6	2584	2384	"		229	9.6	2368	2109	"
	179	9.5	2485	2379	"		230	9.4	2361	2108	"
	180	9.5	2586	2372	"		231	9.5	2353	2106	"
	181	9.2	2587	2364	"		232	9.4	2346	2103	"
	182	9.0	2586	2356	"		233	9.4	2340	2100	"
	183	9.1	2585	2348	"		234	9.7	2333	2100	"
	184	9.2	2581	2341	"		235	10.1	2325	2098	"
	185	9.3	2581	2333	"		236	9.8	2318	2097	"
	186	9.1	2579	2326	"		237	9.5	2310	2095	"
	187	9.1	2582	2319	"		238	14.0	2342	2401	0.00
	188	9.3	2580	2312	"		239	14.0	2349	2405	"
	189	9.4	2581	2306	"		240	14.3	2357	2407	"
	190	9.5	2580	2298	"		241	14.6	2364	2410	"
	191	9.5	2576	2292	"		242	10.5	2361	2609	+0.04
	192	9.6	2571	2285	"		243	10.6	2356	2603	"
	193	9.6	2566	2280	"		244	10.5	2352	2597	"
	194	9.5	2560	2274	"		245	10.7	2348	2591	"
	195	9.5	2556	2268	"		246	10.8	2344	2585	"
	196	9.4	2552	2261	"		247	10.8	2340	2579	"
	197	9.5	2548	2254	"		248	11.0	2336	2573	"
	198	9.3	2543	2248	"		249	10.9	2332	2567	"
	199	9.4	2536	2242	"		250	10.6	2320	2551	"
	200	9.6	2531	2236	"		251	12.0	2248	2437	+0.02
	201	9.6	2525	2231	"		252	12.0	2254	2433	"
	202	9.6	2521	2225	"		253	12.1	2260	2429	"
	203	9.6	2515	2219	"		254	12.1	2267	2425	"
	204	9.7	2509	2214	"		255	12.3	2272	2421	"
	205	9.7	2503	2210	"		256	12.5	2276	2418	"
	206	9.8	2499	2211	"		257	11.7	2244	2440	"
	207	9.7	2494	2207	"		258	11.7	2241	2447	"
	208	9.8	2489	2198	"		259	11.9	2248	2444	"
	209	9.8	2483	2193	"		260	11.8	2253	2450	"
	210	9.7	2478	2187	"		261	10.8	2257	2456	"
	211	9.6	2474	2181	"		262	10.5	2261	2462	"
	212	9.6	2471	2175	"		263	10.9	2266	2469	"
	213	9.5	2466	2168	"		264	11.2	2270	2475	"
	214	9.7	2466	2161	"		265	11.2	2274	2481	"
	215	10.1	2463	2154	"		266	10.9	2279	2487	"
	216	9.7	2461	2150	"		267	9.5	2182	2040	-0.03
	217	9.8	2458	2143	"		268	9.5	2188	2042	"
	218	9.8	2456	2135	"		269	9.6	2195	2044	"
	219	9.7	2445	2120	"		270	9.5	2202	2046	"
	220	9.8	2438	2120	"		271	9.5	2208	2048	"
	221	9.7	2431	2119	"		272	9.6	2216	2051	"
	222	9.4	2422	2118	"		273	9.7	2223	2053	"
	223	9.5	2414	2118	"		274	10.3	2222	2072	"
	224	9.5	2407	2117	"		275	10.0	2225	2065	"
	225	9.4	2399	2116	"		276	9.8	2227	2059	"

D.	277	9.5	2230	2052	–0.03
	278	9.4	2232	2045	"
	279	9.6	2235	2037	"
	280	9.3	2237	2031	"
	281	9.5	2239	2025	"
	282	9.7	2300	2093	0.00
	283	9.8	2293	2091	"
	284	9.8	2285	2089	"
	285	9.8	2278	2088	"
	286	9.8	2271	2086	"
	287	9.9	2264	2085	"
	288	9.9	2777	2852	+0.06
	289	9.9	2786	2852	"
	290	9.9	2793	2853	"
	291	10.0	2801	2855	"
	292	10.1	2808	2856	"
	293	9.9	2815	2856	"
	294	9.8	2821	2856	"
	295	9.9	2828	2858	"
	296	10.0	2834	2856	"
	297	9.8	2843	2856	"
	298	9.8	2847	2861	"
	299	9.8	2851	2867	"
	300	9.9	2855	2873	"
	301	9.9	2859	2879	"
	302	10.0	2861	2886	"
	303	10.1	2865	2891	"
	304	9.7	2868	2897	"
	305	9.9	2873	2903	"
	306	9.9	2877	2909	"
	307	10.0	2881	2916	"
	308	10.0	2885	2922	"
	309	10.2	2890	2927	"
	310	10.4	2879	2930	"
	311	10.4	2876	2937	"
	312	9.8	2937	2958	–0.09
	313	9.8	2944	2955	"
	314	9.8	2951	2951	"
	315	9.7	2957	2946	"
	316	9.7	2963	2941	"
	317	9.8	2969	2938	"
	318	9.7	2977	2935	"
	319	9.6	2985	2933	"
	320	9.5	2992	2931	"
	321	9.5	2998	2928	"
	322	9.5	3004	2927	"
	323	9.4	3072	2922	"
	324	9.4	3064	2923	"
	325	9.3	3056	2924	"
	326	9.2	3060	2929	"
	327	9.6	3077	2935	"
D.	328	9.7	3086	2937	–0.09
	329	9.5	3087	2927	"
	330	9.4	3095	2928	"
	331	9.4	3103	2931	"
	332	9.4	3111	2933	"
	333	9.7	3112	2942	"
	334	9.5	3108	2941	"
	335	9.6	3102	2940	"
	336	9.4	3125	2941	"
	337	9.6	3132	2940	"
	338	9.5	3140	2940	"
	339	9.6	3147	2940	"
	340	9.7	3154	2941	"
	341	9.6	3165	2947	"
	342	9.3	3172	2951	"
	343	9.4	3179	2955	"
	344	9.5	3197	2955	"
	345	9.3	3205	2955	"
	346	9.3	3212	2955	"
	347	9.1	3221	2955	"
	348	9.0	3243	2943	"
	349	9.0	3251	2944	"
	350	8.8	3258	2941	"
	351	8.9	3265	2940	"
	352	9.1	3273	2939	"
	353	8.9	3281	2938	"
	354	8.9	3288	2936	"
	355	8.7	3295	2934	"
	356	8.6	3301	2933	"
	357	8.6	3308	2932	"
	358	8.5	3319	2943	"
	359	8.6	3324	2942	"
	360	8.6	3328	2940	"
	361	8.5	3315	2944	"
	362	8.5	3310	2945	"
	363	8.6	3305	2946	"
	364	8.7	3300	2948	"
	365	10.8	2060	2275	–0.03
	366	11.1	2056	2283	"
	367	11.3	2044	2289	"
	368	16.2	2454	2313	"
	369	16.2	2445	2314	"
	370	16.3	2436	2313	"
	371	16.5	2432	2313	"
	372	24.2	2272	2283	"
	373	24.3	2293	2287	"
	374	24.3	2295	2282	"
	375	19.7	3686	2979	"
	376	19.9	3680	2982	"
	377	19.6	3674	2983	"
	378	17.3	2008	2287	+0.10

D.	379	19.4	1998	2293	+0.10	D.	430	25.3	2108	2110	+0.02
	380	19.4	1997	2290	"		431	25.3	2113	2112	"
	381	18.8	1989	2272	"		432	25.4	2118	2113	"
	382	20.1	1976	2256	"		433	25.6	2122	2115	"
	383	19.4	1970	2254	"		434	20.5	2103	2091	"
	384	18.8	1968	2245	"		435	20.5	2106	2093	"
	385	18.8	1962	2242	"		436	20.5	2110	2094	"
	386	10.1	1889	2096	-0.03		437	20.5	2114	2095	"
	387	9.7	1896	2093	"		438	20.6	2118	2096	"
	388	9.8	1903	2092	"		439	11.8	2212	2089	"
	389	10.2	1846	2089	0.00		440	11.7	2207	2090	"
	390	10.2	1851	2089	"		441	11.7	2202	2090	"
	391	9.6	1858	2090	"		442	11.9	2202	2094	"
	392	9.5	1864	2091	"		443	11.7	2214	2092	"
	393	9.6	1871	2091	"		444	12.1	2218	2093	"
	394	9.7	1878	2096	"		445	12.1	2223	2093	"
	395	10.7	1842	2090	"		446	11.9	2228	2092	"
	396	10.2	1841	2087	"		447	11.8	2233	2092	"
	397	10.3	1837	2091	"		448	11.6	2238	2091	"
	398	10.1	1830	2091	"		449	25.2	2205	2116	"
	399	9.7	1822	2092	"		450	25.1	2210	2116	"
	400	9.9	1813	2092	"		451	25.2	2214	2117	"
	401	9.8	1805	2093	"		452	25.1	2218	2118	"
	402	16.5	2360	2305	+0.05		453	25.2	2223	2119	"
	403	16.7	1843	2119	+0.02		454	25.0	2228	2120	"
	404	16.8	1838	2118	"		455	24.9	2232	2121	"
	405	16.6	1827	2119	"		456	24.9	2237	2121	"
	406	16.4	1819	2119	"		457	25.0	2242	2121	"
	407	16.4	1811	2120	"		458	25.2	2201	2117	"
	408	16.2	1804	2124	"		459	25.3	2195	2117	"
	409	16.4	1847	2119	"		460	25.5	2189	2117	"
	410	16.5	1852	2119	"		461	25.6	2184	2117	"
	411	16.2	1856	2121	"		462	25.6	2178	2118	"
	412	0.7	3365	2923	+0.18		463	25.5	2173	2118	"
	413	0.7	3369	2925	"		464	24.5	2286	2121	0.00
	414	0.9	3373	2926	"		465	25.1	2281	2121	"
	415	0.9	3378	2926	"		466	24.6	2276	2120	"
	416	0.9	3383	2927	"		467	24.7	2270	2120	"
	417	0.6	3390	2919	"		468	24.1	2264	2120	"
	418	1.3	3387	2928	"		469	24.7	2259	2120	"
	419	0.8	3362	2925	"		470	24.7	2254	2121	"
	420	0.9	3358	2927	"		471	24.5	2250	2121	"
	421	0.9	3353	2928	"		472	22.5	2436	2198	-0.03
	422	1.0	3349	2928	"		473	22.9	2431	2195	"
	423	1.2	3345	2929	"		474	23.6	2428	2192	"
	424	25.3	2089	2109	+0.02		475	24.4	2427	2188	"
	425	25.3	2085	2110	"		476	23.8	2425	2184	"
	426	25.3	2080	2111	"		477	23.9	2424	2181	"
	427	25.4	2095	2110	"		478	24.1	2422	2178	"
	428	25.3	2099	2111	"		479	24.1	2420	2174	"
	429	25.4	2103	2110	"		480	23.8	2419	2168	"

D.	481	24.1	2417	2161	-0.03	D.	532	21.2	3116 2966	+0.01
	482	24.6	2489	2230	0.00		533	21.9	3121 2967	"
	483	24.3	2487	2233	"		534	21.9	3125 2968	"
	484	24.7	2492	2236	"		535	21.8	3132 2966	"
	485	24.3	2496	2238	"		536	21.4	3138 2966	"
	486	23.9	2501	2237	"		537	21.7	3142 2966	"
	487	22.7	2505	2241	"		538	25.3	3145 2972	+0.10
	488	23.6	2540	2310	"		539	25.2	3149 2972	"
	489	23.5	2535	2315	"		540	25.7	3154 2973	"
	490	23.3	2530	2319	"		541	22.2	3148 2965	"
	491	23.0	2526	2319	"		542	21.8	3149 2964	"
	492	23.5	2521	2319	"		543	27.6	3178 2978	"
	493	23.4	2517	2318	"		544	27.9	3173 2978	"
	494	27.1	2522	2312	"		545	28.3	3168 2978	"
	495	27.1	2518	2312	"		546	28.6	3163 2979	"
	496	27.5	2514	2312	"		547	28.9	3159 2979	"
	497	13.1	2551	2365	+0.02		548	27.7	3190 2978	"
	498	13.1	2556	2366	"		549	27.7	3186 2978	"
	499	13.2	2561	2367	"		550	27.7	3182 2978	"
	500	13.1	2533	2342	"		551	27.7	3195 2978	"
	501	11.5	2531	2346	"		552	27.7	3199 2977	"
	502	10.9	2529	2349	"		553	28.0	3207 2976	"
	503	10.4	2526	2355	"		554	27.5	3210 2975	"
	504	10.3	2524	2360	"		555	27.3	3245 2974	"
	505	10.3	2521	2364	"		556	27.3	3250 2974	"
	506	11.3	2529	2350	"		557	27.7	3255 2973	"
	507	11.2	2533	2354	"		558	28.0	3261 2972	"
	508	11.5	2525	2346	"		559	28.3	3266 2971	"
	509	11.6	2520	2343	"		560	32.1	3241 2990	"
	510	11.6	2516	2340	"		561	31.9	3245 2989	"
	511	11.9	2512	2337	"		562	31.8	3250 2988	"
	512	11.5	2508	2334	"		563	31.6	3254 2987	"
	513	11.8	2504	2332	"		564	31.8	3259 2987	"
	514	11.9	2500	2330	"		565	31.9	3264 2987	"
	515	12.4	2498	2322	"		566	32.1	3268 2987	"
	516	12.8	2495	2321	"		567	31.6	3273 2988	"
	517	13.4	2492	2320	"		568	13.7	2154 2335	+0.02
	518	22.7	3046	2972	+0.01		569	13.8	2158 2339	"
	519	22.6	3049	2972	"		570	13.5	2162 2342	"
	520	22.7	3051	2973	"		571	13.4	2165 2344	"
	521	22.1	3055	2973	"		572	13.5	2169 2347	"
	522	21.9	3059	2972	"		573	13.4	2173 2350	"
	523	22.3	3064	2971	"		574	13.5	2177 2352	"
	524	21.6	3069	2970	"		575	13.5	2182 2354	"
	525	20.9	3074	2968	"		576	13.9	2190 2355	"
	526	21.0	3079	2967	"		577	14.1	2194 2357	"
	527	21.5	3084	2965	"		578	14.1	2199 2358	"
	528	21.3	3089	2964	"		579	13.7	2204 2360	"
	529	22.2	3096	2965	"		580	13.6	2209 2362	"
	530	21.6	3103	2965	"		581	13.6	2214 2363	"
	531	21.7	3107	2965	"		582	13.9	2219 2364	"

D.	583	13.7	2225	2366	+0.02
	584	15.4	2107	2376	+0.08
	585	15.5	2103	2373	"
	586	15.5	2098	2371	"
	587	15.4	2093	2369	"
	588	15.5	2088	2366	"
	589	15.5	2092	2360	"
	590	15.5	2087	2357	"
	591	15.7	2082	2353	"
	592	16.1	2073	2346	"
	593	15.8	2063	2340	"
	594	15.9	2059	2339	"
	595	16.4	2055	2338	"
	596	15.1	2114	2381	"
	597	15.4	2118	2384	"
	598	14.6	2122	2388	"
	599	15.0	2132	2390	"
	600	14.8	2132	2392	"
	601	14.8	2133	2395	"
	602	14.8	2135	2400	"
	603	14.6	2137	2405	"
	604	14.8	2139	2409	"
	605	14.8	2141	2413	"
	606	14.9	2143	2418	"
	607	14.6	2145	2423	"
	608	14.8	2150	2432	+0.02
	609	15.1	2150	2436	"
	610	14.9	2150	2440	"
	611	21.2	2151	2471	"
	612	21.9	2147	2469	"
	613	22.0	2143	2467	"
	614	14.8	2152	2444	"
	615	15.0	2155	2451	"
	616	15.4	2158	2454	"
	617	15.1	2162	2459	"
	618	18.4	2220	2578	+0.05
	619	18.7	2223	2581	"
	620	11.0	2245	2579	"
	621	10.6	2247	2583	"
	622	10.5	2250	2587	"
	623	10.9	2252	2591	"
	624	10.4	2255	2595	"
	625	10.1	2258	2598	"
	626	10.4	2262	2603	"
	627	10.6	2267	2606	"
	628	10.6	2270	2610	"
	629	10.9	2275	2612	"
	630	10.5	2281	2616	"
	631	10.5	2285	2618	"
	632	10.9	2288	2621	"
	633	11.0	2422	2802	"

D.	634	10.8	2418	2799	+0.05
	635	10.5	2415	2797	"
	636	10.5	2411	2794	"
	637	10.8	2426	2805	"
	638	10.9	2431	2807	"
	639	10.9	2435	2810	"
	640	11.0	2402	2786	"
	641	10.8	2398	2785	"
	642	10.6	2394	2783	"
	643	10.5	2391	2781	"
	644	10.5	2387	2778	"
	645	10.5	2383	2776	"
	646	10.7	2380	2773	"
	647	10.7	2378	2770	"
	648	23.6	2534	2745	+0.09
	649	23.8	2530	2749	"
	650	24.0	2527	2753	"
	651	24.0	2523	2757	"
	652	23.4	2543	2744	"
	653	23.5	2549	2744	"
	654	23.8	2553	2748	"
	655	23.1	2536	2762	"
	656	19.9	2559	2767	"
	657	19.6	2564	2766	"
	658	19.1	2570	2766	"
	659	18.5	2575	2766	"
	660	14.4	2527	2776	+0.02
	661	14.0	2532	2776	"
	662	14.3	2537	2777	"
	663	20.9	2501	2730	+0.13
	664	20.7	2506	2731	"
	665	20.6	2511	2730	"
	666	20.8	2515	2730	"
	667	15.1	2529	2701	"
	668	15.6	2523	2707	"
	669	15.9	2522	2714	"
	670	16.0	2523	2721	"
	671	15.6	2529	2726	"
	672	12.5	2542	2701	"
	673	12.7	2541	2708	"
	674	12.6	2541	2714	"
	675	12.9	2545	2719	"
	676	12.6	2551	2722	"
	677	12.6	2556	2724	"
	678	13.2	2774	2929	+0.02
	679	12.9	2777	2927	"
	680	12.8	2779	2922	"
	681	12.9	2780	2917	"
	682	12.9	2781	2912	"
	683	12.8	2872	2907	"
	684	12.5	2835	2897	+0.03

D. 685	12.6	2836	2904	+0.03
686	13.0	2839	2910	"
687	12.5	2843	2918	"
688	12.7	2850	2922	"
689	12.8	2838	2913	"
690	9.3	2133	1983	+0.06
691	9.3	2132	1993	"
692	9.4	2067	2023	-0.02
693	9.8	2067	2016	"
694	9.5	2067	2011	"
695	10.3	2649	2939	+0.10
696	10.3	2647	2943	"
697	10.3	2646	2947	"
698	11.4	2644	2951	"
699	10.2	2653	2931	"
700	10.1	2656	2924	"
701	10.0	2663	2908	"
702	10.1	2666	2901	"
703	10.0	2668	2895	"
704	10.0	2671	2889	"
705	10.4	2678	2874	"
706	10.1	2681	2867	"
707	9.9	2685	2860	"
708	9.8	2691	2847	"
709	9.6	2694	2849	"
710	9.7	2698	2832	"
711	9.8	2701	2825	"
712	9.7	2704	2817	"
713	9.8	2708	2811	"
714	9.8	2712	2802	"
715	9.9	2717	2790	"
716	9.9	2722	2780	"
717	12.2	2500	2520	-0.03
718	12.2	2507	2519	"
719	6.3	1803	2067	0.00
720	6.6	1810	2063	"
721	6.4	1816	2059	"
722	6.5	1824	2055	"
723	6.4	1830	2051	"
724	5.7	1829	2038	"
725	5.5	1825	2040	"
726	5.8	1822	2043	"
727	5.6	1818	2046	"
728	12.4	2515	2517	-0.03
729	11.9	2498	2516	"
730	11.9	2490	2516	"
731	11.9	2482	2515	"
732	11.8	2475	2517	"
733	11.8	2468	2518	"
734	11.9	2460	2518	"
735	11.9	2438	2521	"
D. 736	6.2	1887	2033	+0.03
737	6.4	1879	2035	"
738	6.3	1871	2037	"
739	6.6	1863	2039	"
740	6.6	1856	2041	"
741	6.6	1848	2043	"
742	6.5	1903	2027	"
743	6.5	1909	2022	"
744	6.3	1916	2019	"
745	6.2	1923	2015	"
746	6.2	1931	2012	"
747	6.4	1938	2010	"
748	6.5	1946	2008	"
749	5.5	1942	2002	"
750	5.4	1934	2003	"
751	5.3	1926	2003	"
752	5.3	1919	2006	"
753	5.2	1912	2009	"
754	4.4	1906	2005	"
755	4.6	1913	2002	"
756	4.4	1923	1999	"
757	4.3	1931	1995	"
758	4.3	1939	1992	"
759	4.6	1946	1990	"
760	4.6	1953	1988	"
761	4.6	1960	1987	"
762	3.4	1955	1980	"
763	3.5	1948	1980	"
764	3.4	1939	1982	"
765	3.4	1931	1984	"
766	3.4	1923	1985	"
767	3.3	1915	1987	"
768	3.2	1908	1991	"
769	3.3	1902	1994	"
770	3.7	1968	1979	+0.02
771	3.6	1961	1980	"
772	3.4	1971	1978	"
773	3.4	1978	1975	"
774	3.3	1985	1973	"
775	3.3	1993	1971	"
776	3.3	2000	1968	"
777	1.5	1973	1941	"
778	1.4	1981	1941	"
779	1.2	1988	1940	"
780	1.3	1995	1940	"
781	1.4	2001	1943	"
782	4.7	2016	1969	"
783	4.5	2025	1974	"
784	4.5	2034	1972	"
785	4.7	2041	1969	"
786	4.6	2048	1966	"

D.	787	4.4	2055	1963	+0.02
	788	4.3	2062	1960	"
	789	3.1	2055	1951	"
	790	3.4	2048	1954	"
	791	3.4	2041	1956	"
	792	3.5	2034	1959	"
	793	3.4	2026	1960	"
	794	3.4	2020	1962	"
	795	3.3	2013	1963	"
	796	3.4	2006	1964	"
	797	10.0	2544	2458	0.00
	798	9.9	2550	2463	"
	799	9.9	2556	2468	"
	800	10.0	2562	2473	"
	801	10.0	2569	2478	"
	802	9.7	2574	2484	"
	803	9.7	2579	2490	"
	804	9.7	2584	2497	"
	805	9.7	2584	2504	"
	806	9.7	2582	2511	"
	807	9.9	2580	2517	"
	808	9.8	2578	2524	"
	809	9.9	2572	2532	"
	810	9.8	2567	2538	"
	811	10.0	2727	2769	-0.11
	812	9.9	2730	2762	"
	813	9.8	2734	2755	"
	814	9.8	2737	2747	"
	815	9.8	2741	2738	"
	816	9.8	2745	2730	"
	817	9.9	2748	2724	"
	818	9.8	2751	2717	"
	819	9.6	2754	2710	"
	820	9.6	2757	2704	"
	821	9.7	2761	2697	"
	822	9.8	2764	2690	"
	823	9.7	2767	2682	"
	824	9.6	2771	2675	"
	825	9.4	2773	2670	"
	826	9.4	2776	2663	"
	827	9.3	2780	2656	"
	828	9.4	2784	2646	"
	829	9.4	2786	2642	"
	830	19.2	3504	3060	0.00
	831	19.0	3507	3058	"
	832	9.1	2807	2597	"
	833	9.1	2811	2590	"
	834	8.8	2814	2582	"
	835	9.1	2816	2578	"
	836	10.5	2562	2531	"
	837	10.5	2555	2533	"
D.	838	10.4	2548	2536	0.00
	839	10.5	2541	2539	"
	840	10.6	2535	2541	"
	841	10.5	2531	2546	"
	842	10.7	2523	2547	"
	843	10.5	2516	2548	"
	844	10.6	2509	2549	"
	845	10.5	2502	2550	"
	846	10.1	2500	2554	"
	847	10.3	2508	2554	"
	848	11.6	2435	2586	-0.04
	849	11.7	2433	2577	"
	850	12.2	2428	2570	"
	851	12.2	2422	2565	"
	852	12.4	2415	2561	"
	853	12.5	2408	2558	"
	854	12.5	2401	2555	"
	855	12.6	2391	2549	"
	856	12.5	2387	2547	"
	857	12.4	2380	2543	"
	858	11.9	2375	2547	"
	859	11.4	2371	2549	"
	860	11.5	2364	2553	"
	861	11.1	2357	2557	"
	862	10.9	2350	2561	"
	863	10.9	2340	2566	"
	864	10.9	2336	2569	"
	865	10.9	2330	2572	"
	866	10.5	2324	2577	"
	867	10.8	2319	2579	"
	868	10.8	2311	2581	"
	869	10.7	2300	2591	"
	870	10.6	2294	2595	"
	871	10.5	2287	2599	"
	872	10.2	2281	2603	"
	873	10.4	2274	2607	"
	874	10.6	2267	2611	"
	875	10.8	2344	2661	+0.02
	876	10.6	2339	2667	"
	877	10.5	2333	2671	"
	878	10.1	2328	2677	"
	879	10.6	2322	2682	"
	880	11.1	2316	2688	"
	881	12.2	2313	2691	"
	882	10.4	2350	2656	"
	883	10.4	2356	2650	"
	884	10.4	2359	2647	"
	885	9.9	2366	2640	+0.04
	886	10.5	2373	2634	"
	887	10.5	2378	2630	"
	888	10.4	2383	2625	"

D.	889	10.4	2388	2620	+0.04
	890	10.5	2394	2614	"
	891	10.8	2397	2610	"
	892	10.7	2399	2608	"
	893	10.7	2405	2603	"
	894	11.2	2410	2598	"
	895	11.3	2415	2593	"
	896	11.6	2419	2588	"
	897	11.7	2424	2584	"
	898	11.4	2428	2580	"
	899	11.7	2431	2577	"
	900	12.3	2434	2574	"
	901	12.7	2436	2572	"
	902	10.5	2467	2737	+0.02
	903	10.4	2471	2736	"
	904	10.6	2476	2734	"
	905	10.9	2480	2732	"
	906	11.7	2484	2730	"
	907	10.3	2459	2740	"
	908	10.1	2454	2745	"
	909	10.1	2447	2748	"
	910	10.1	2442	2748	"
	911	9.9	2437	2753	"
	912	10.0	2430	2755	"
	913	10.1	2423	2759	"
	914	10.1	2416	2762	"
	915	10.3	2410	2765	"
	916	10.1	2404	2768	"
	917	10.1	2398	2771	"
	918	10.4	2392	2774	"
	919	10.4	2388	2776	"
	920	11.0	2384	2778	"
	921	11.9	2324	2428	0.00
	922	12.1	2316	2429	"
	923	12.1	2309	2424	"
	924	12.3	2300	2422	"
	925	12.6	2292	2420	"
	926	19.8	3599	3011	-0.01
	927	19.8	3591	3013	"
	928	19.8	3582	3018	"
	929	19.8	3574	3021	"
	930	19.4	3567	3025	"
	931	19.7	3560	3029	"
	932	19.0	3467	3094	0.00
	933	18.8	3474	3091	"
	934	19.2	3481	3084	"
	935	19.0	3488	3080	"
	936	19.0	3495	3076	"
	937	18.8	3501	3067	"

APPENDIX II

The following list includes all carseland bores sunk by the writer, and gives the National Grid reference (G.R.) and ground level (G.L.) of each bore, and the depths in centimetres and altitudes in metres above Ordnance Datum of each change in stratigraphy.

AREA B

BB-1 — G.R.: NO 1420 1657 — G.L.: 9.9m O.D.

depth	alt.	
200	7.9	Grey silty CLAY (carse)
205	7.9	Clay-peat TRANSITION
210	7.8	PEAT
250	7.4	Pale grey mic.*silty fine SAND NOT BOTTOMED

BB-2 — G.R.: NO 1423 1661 — G.L.: 10.0m O.D.

depth	alt.	
293	7.0	Grey CLAY (carse)
300	7.0	Clay-peat TRANSITION
309	6.9	Dry compact PEAT
330	6.7	Pale grey mic. silty fine SAND NOT BOTTOMED

BB-3 — G.R.: NO 1427 1665 — G.L.: 9.8 m O.D.

depth	alt.	
288	6.9	Grey silty CLAY (carse)
293	6.9	Clay-peat TRANSITION
310	6.7	Dry, compact PEAT
318	6.6	Peat-sand TRANSITION
330	6.5	Grey mic. silty fine SAND NOT BOTTOMED

BB-4 — G.R.: NO 1433 1672 — G.L.: 10.2m O.D.

depth	alt.	
327	6.9	Grey silty CLAY (carse)
331	6.9	Clay-peat TRANSITION
337	6.8	Compact PEAT
353	6.7	Grey mic. fine sandy SILT
366	6.6	Pale bluish-grey clayey SILT NOT BOTTOMED

BB-5 — G.R.: NO 1446 1685 — G.L.: 10.0m O.D.

depth	alt.	
368	6.3	Grey silty CLAY (carse)
373	6.2	Clay-peat TRANSITION
393	6.0	Compact PEAT
397	6.0	Peat-sand TRANSITION
412	5.8	Yellowish-grey mic. silty fine SAND NOT BOTTOMED

BB-6 — G.R.: NO 1476 1718 — G.L.: 9.9m O.D.

depth	alt.	
502	4.9	Grey silty CLAY (carse)
506	4.8	Clay-peat TRANSITION
538	4.5	Tough compact PEAT
550	4.4	Steel-grey mic. fine SAND NOT BOTTOMED

BB-7 — G.R.: NO 1461 1700 — G.L.: 9.8m O.D.

depth	alt.	
470	5.1	Grey silty CLAY (carse)
480	5.0	Grey mic. fine SAND NOT BOTTOMED

BB-8 — G.R.: NO 1498 1739 — G.L.: 10.1m O.D.

depth	alt.	
504	5.0	Bluish-grey silty CLAY (carse)
508	5.0	Clay-peat TRANSITION
537	4.7	Tough compact PEAT
544	4.6	Peat-silt TRANSITION
580	4.3	Buff fine sandy SILT changing to mic. silty fine SAND NOT BOTTOMED

* See p.339 for abbreviations.

BB-9		G.R.: NO 1488 1731 G.L.: 9.9m
489	5.0	Bluish-grey silty CLAY (carse)
491	5.0	Clay-peat TRANSITION
528	4.6	Tough, compact wood PEAT
543	4.4	Grey mic. silty fine SAND
		NOT BOTTOMED

BB-10		G.R.: NO 1613 1905 G.L.: 9.7m
159	8.1	Silty CLAY or clayey SILT (carse)
240	7.3	F.soft PEAT
244	7.3	Peat-silt TRANSITION
254	7.2	Yellowish-grey v.mic. silty fine SAND & sandy SILT
		NOT BOTTOMED

BB-11		G.R.: NO 1615 1901 G.L.: 9.8m
294	6.8	Silty CLAY (carse)
306	6.7	Clay-peat TRANSITION
407	5.7	F.compact PEAT
426	5.5	Grey mic. silty fine SAND
		NOT BOTTOMED

BB-12		G.R.: NO 1617 1897 G.L.: 9.5m
268	6.9	Silty CLAY (carse)
277	6.8	Clay-peat TRANSITION
292	6.6	Dry compact PEAT
310	6.4	Grey mic. v.gritty fine SAND
		NOT BOTTOMED

BB-13		G.R.: NO 1621 1888 G.L.: 9.9m
120	8.7	Silty CLAY (carse)
122	8.7	Peaty VEG.REMS.
125	8.7	Brownish-grey silty CLAY
190	8.0	Brown-grey SAND & fine GRAVEL, bec. reddish. More clayey & mic. below 164
		NOT BOTTOMED

BB-14		G.R.: NO 1619 1893 G.L.: 9.9m
256	7.4	Sandy silty CLAY (carse)
269	7.2	Clay-peat TRANSITION
325	6.7	Firm compact PEAT
330	6.6	Grey mic. silty fine SAND
		NOT BOTTOMED

BB-15		G.R.: NO 1453 1693 G.L.: 9.8m
370	6.1	Blue-grey silty CLAY (carse)
373	6.1	Clay-peat TRANSITION
392	5.9	Woody PEAT
405	5.8	Brown-grey mic. silty fine SAND
		NOT BOTTOMED

BB-16		G.R.: NO 1447 1686 G.L.: 9.9m
355	6.3	Blue-grey silty CLAY (carse)
360	6.3	Clay-peat TRANSITION
376	6.1	PEAT
390	6.0	Grey mic. silty fine SAND/fine sandy SILT
		NOT BOTTOMED

BB-17		G.R.: NO 1440 1679 G.L.: 10.0m
356	6.4	Blue-grey silty CLAY (carse)
360	6.4	Clay-peat TRANSITION
381	6.2	F.tough compact PEAT
385	6.1	Pale blue-grey mic. CLAY
400	6.0	Grey-Brown mic. silty fine SAND/fine sandy SILT
		NOT BOTTOMED

BB-18		G.R.: NO 1437 1675 G.L.: 9.9m
310	6.8	Blue-grey silty CLAY (carse)
312	6.8	Clay-peat TRANSITION
324	6.7	PEAT
340	6.5	Pale grey mic. silty fine SAND/sandy SILT
		NOT BOTTOMED

BB-19		G.R.: NO 1458 1697 G.L.: 9.9m
425	5.7	Blue-grey silty CLAY (carse)
456	5.4	Tough woody PEAT
465	5.3	Grey mic. fine SAND
		NOT BOTTOMED

BB-20 G.R.: NO 1456 1696
G.L.: 10.0m

430 5.7 Grey silty CLAY (carse)
432 5.7 Clay-peat TRANSITION
466 5.4 Tough woody PEAT
468 5.3 Grey mic. silty fine SAND
NOT BOTTOMED

BB-21 G.R.: NO 1454 1694
G.L.: 9.9m

400 5.9 Blue-grey silty CLAY (carse)
440 5.5 Tough dk.brown woody PEAT
443 5.5 Peat-silt TRANSITION
475 5.1 Dk. grey mic. fine sandy clayey SILT
NOT BOTTOMED

BB-22 G.R.: NO 1438 1677
G.L.: 9.9m

332 6.5 Blue-grey silty CLAY (carse)
336 6.5 Clay-peat TRANSITION
357 6.3 Tough woody PEAT
390 6.0 Dk. grey mic. fine sandy clayey SILT
NOT BOTTOMED

BB-23 G.R.: NO 1463 1704
G.L.: 10.1m

450 5.6 Grey silty CLAY (carse)
454 5.6 Clay-peat TRANSITION
482 5.3 Tough, compact, v.woody PEAT
500 5.1 Pale blue-grey silty fine SAND
NOT BOTTOMED

BB-24 G.R.: NO 1466 1708
G.L.: 10.1m

477 5.3 Grey silty CLAY (carse)
483 5.2 Clay-peat TRANSITION
514 4.9 Tough woody PEAT
525 4.8 Pale blue-grey mic. fine SAND
NOT BOTTOMED

BB-25 G.R.: NO 1540 1783
G.L.: 9.9m

604 3.9 Grey silty CLAY/clayey SILT (carse)
608 3.8 Silt-peat TRANSITION
638 3.5 V.tough woody PEAT
644 3.5 Peat-sand TRANSITION
660 3.3 Pale grey mic. gritty fine SAND
NOT BOTTOMED

BB-26 G.R.: NO 1522 1768
G.L:: 10.2m

504 5.2 Grey silty CLAY (carse)
509 5.1 Clay-peat TRANSITION
525 4.9 Woody PEAT
545 4.7 Grey mic. fine SAND
NOT BOTTOMED

BB-27 G.R.: NO 1529 1776
G.L.: 10.2m

597 4.2 Blue-grey silty CLAY/clayey SILT
600 4.2 Clay-peat TRANSITION
624 3.9 Compact woody PEAT
635 3.8 Grey mic. gritty fine-med SAND
NOT BOTTOMED

BB-28 G.R.: NO 1525 1772
G.L.: 10.0m

615 3.9 Grey silty CLAY bec. SILT (carse)
618 3.9 Silt-peat TRANSITION
652 3.5 V.tough compact woody PEAT
665 3.4 Pale grey mic. fine-med SAND
NOT BOTTOMED

BB-29 G.R.: NO 1551 1799
G.L.: 9.5m

860 0.9 Blue-grey silty CLAY/clayey SILT (carse)
NOT BOTTOMED

BB-30 G.R.: NO 1568 1813
G.L.: 10.0m

699 3.0 Grey silty CLAY/clayey SILT (carse); lens of fine-med SAND 598-600; bec v. firm, chunks of wood 668-698
NOT BOTTOMED

BB-31 G.R.: NO 1626 1651
G.L.: 8.7m

356	5.2	F. soft blue-grey silty CLAY (carse)
434	4.4	Tough compact woody PEAT
446	4.3	Grey mic. silty fine SAND/fine sandy SILT
		NOT BOTTOMED

BB-32 G.R.: NO 1627 1649
G.L.: 9.1m

331	5.8	Grey silty CLAY (carse)
360	5.5	Tough woody PEAT
365	5.5	V. tough grey mic. silty fine SAND
		NOT BOTTOMED

BB-33 G.R.: NO 1626 1656
G.L.: 9.5m

516	4.4	Blue-grey silty CLAY (carse)
564	3.9	V. tough woody PEAT
567	3.9	Peat/silt TRANSITION
575	3.8	V. tough grey mic. fine sandy clayey SILT
		NOT BOTTOMED

BB-34 G.R.: NO 1626 1660
G.L.: 9.7m

550	4.2	Blue-grey silty CLAY (carse)
554	4.2	Clay-peat TRANSITION
613	3.6	Tough compact woody PEAT
615	3.6	Grey mic. fine SAND
		NOT BOTTOMED

BB-35 G.R.: NO 1625 1669
G.L.: 9.8m

514	4.7	Blue-grey silty CLAY (carse); peaty veg. remains below 498.
525	4.6	V. tough brown-grey mic. silty fine SAND
		NOT BOTTOMED

BB-36 G.R.: NO 1624 1679
G.L.: 10.0m

570	4.3	Grey silty CLAY (carse) with abundant veg. rems. below c.500
580	4.2	V. tough pale grey mic. fine-med SAND
		NOT BOTTOMED

BB-37 G.R.: NO 1623 1688
G.L.: 9.7 m

529	4.4	Grey silty CLAY (carse)
573	3.9	Tough fibrous PEAT
577	3.9	Pale grey mic. fine-med SAND
		NOT BOTTOMED

BB-38 G.R.: NO 1621 1701
G.L.: 9.6m

503	4.6	Grey silty CLAY (carse)
535	4.2	V. tough fibrous woody PEAT
		NOT BOTTOMED

BB-39 G.R.: NO 1672 1667
G.L.: 9.2m

371	5.5	Grey silty CLAY (carse)
374	5.5	Clay-peat TRANSITION
465	4.6	Woody PEAT
468	4.6	Grey v. mic. silty fine SAND
		NOT BOTTOMED

BB-40 G.R.: NO 1670 1678
G.L.: 9.6m

517	4.5	Grey silty CLAY (carse)
519	4.5	Clay-peat TRANSITION
594	3.7	Woody PEAT
602	3.6	Grey mic. silty fine SAND
604	3.6	Grey mic. fine SAND
		NOT BOTTOMED

BB-41 G.R.: NO 1669 1683
G.L.: 9.7m

531	4.4	Blue-grey silty CLAY (carse)
536	4.4	Clay-peat TRANSITION
614	3.6	Woody PEAT
620	3.5	Grey mic. silty fine SAND bec. fine SAND
		NOT BOTTOMED

BB-42 G.R.: NO 1671 1673
G.L.: 9.4 m

460	4.8	Blue-grey silty CLAY (carse)
579	3.6	V. woody PEAT
585	3.6	V. tough grey mic. silty fine SAND NOT BOTTOMED

BB-43 G.R.: NO 1667 1696
G.L.: 9.6 m

508	4.5	Grey silty CLAY (carse)
512	4.5	Clay-peat TRANSITION
577	3.8	Compact woody PEAT
590	3.7	Grey mic. fine SAND NOT BOTTOMED

BB-44 G.R.: NO 1665 1706
G.L.: 9.3 m

495	4.4	Grey silty CLAY (carse)
500	4.3	Clay-peat TRANSITION
555	3.8	Compact woody PEAT
560	3.7	V. tough grey mic. fine SAND. NOT BOTTOMED

BB-45 G.R.: NO 1863 1767
G.L.: 9.4 m

440	5.0	Grey silty CLAY (carse)
460	4.8	Grey mic. silty fine SAND. NOT BOTTOMED

BB-46 G.R.: NO 1862 1769
G.L.: 9.2 m

570	3.5	Grey silty CLAY (carse)
605	3.1	V. tough woody PEAT
610	3.1	Fine SAND. NOT BOTTOMED

BB-47 G.R.: NO 1861 1773
G.L.: 9.5 m

625	3.2	Grey silty CLAY (carse)
627	3.2	Clay-peat TRANSITION
640	3.1	V. tough woody PEAT NOT BOTTOMED

BB-48 G.R.: NO 1857 1762
G.L.: 9.8 m

651	3.3	Grey silty CLAY (carse)
670	3.1	V. tough woody PEAT NOT BOTTOMED

BB-49 G.R.: NO 1850 1800
G.L.: 9.6 m

688	2.8	Grey silty CLAY (carse)
700	2.6	V. tough woody PEAT NOT BOTTOMED

BB-50 G.R.: NO 1227 1857
G.L.: 11.0 m

60	10.4	Sandy SOIL and SAND
112	9.8	Brown-grey silty CLAY (carse)
130	9.7	Grey mic. silty fine SAND. NOT BOTTOMED

BB-51 G.R.: NO 1227 1859
G.L.: 10.6 m

88	9.8	Gritty SOIL & brown-grey silty CLAY (carse)
100	9.6	Grey mic. silty fine SAND. NOT BOTTOMED

BB-52 G.R.: NO 1227 1861
G.L.: 10.6 m

80	9.8	SOIL & brown-grey silty CLAY (carse)
100	9.6	Grey mic. silty fine SAND. NOT BOTTOMED

BB-53 G.R.: NO 1227 1864
G.L.: 10.6 m

154	9.1	Brown-grey silty CLAY (carse)
165	9.0	Brown mic. silty fine SAND. NOT BOTTOMED

BB-54 G.R.: NO 1227 1866
G.L.: 10.6 m

184	8.7	Brown silty CLAY (carse)
195	8.6	Brown mic. silty fine SAND. NOT BOTTOMED

BB-55 G.R.: NO 1227 1869
G.L.: 10.2 m

505	5.1	Grey silty CLAY (carse)
508	5.1	Clay-peat TRANSITION
534	4.8	Compact woody PEAT
538	4.8	Brown-grey mic. silty fine SAND. NOT BOTTOMED

BB-56 G.R.: NO 1228 1874
G.L.: 9.9 m

519	4.8	Grey silty CLAY (carse)
540	4.5	V. peaty SILT/silty PEAT
580	4.1	Grey mic. fine sandy SILT
585	4.1	V. tough silty fine SAND. NOT BOTTOMED

BB-57 G.R.: NO 1228 1879
G.L.: 9.7m

535	4.3	Grey silty CLAY (carse), v. abundant peaty & woody veg. rems. below 500
550	4.2	Grey mic. fine sandy SILT/ silty fine SAND
		NOT BOTTOMED

BB-58 G.R.: NO 1471 1712
G.L.: 10.0m

498	5.0	Grey silty CLAY (carse)
517	4.8	V. compact woody PEAT
529	4.7	Grey mic. silty fine SAND
545	4.5	Pale yellow mic. silty fine SAND
		NOT BOTTOMED

BB-59 G.R.: NO 1627 1875
G.L.: 10.3m

30	10.0	Silty sandy clayey SOIL
91	9.4	Bright yellow med. gritty SAND mixed with pale grey mic. silty fine SAND/fine sandy SILT
		NOT BOTTOMED

AREA C

CB-1 G.R.: NO 0685 1836
G.L.: 11.6m

269	8.9	Brownish-grey sandy CLAY bec. silty CLAY (carse)
282	8.7	Dark grey coarse SAND & fine GRAVEL
		NOT BOTTOMED

CB-2 G.R.: NO 0671 1852
G.L.: 10.9m

230	8.6	Bluish-grey silty CLAY (carse)
254	8.4	Dark grey coarse SAND & fine GRAVEL
		NOT BOTTOMED

CB-3 G.R.: NO 0662 1865
G.L.: 10.6m

305	7.6	Blue-grey mic. silty CLAY with woody rems. at base

Stopped at 305 by pebble or boulder believed to be in gravel matrix

CB-4 G.R.: NO 0653 1875
G.L.: 10.8m

92	9.9	Brownish blue-grey mic. silty CLAY(carse)
160	9.2	Brown medium SAND with some fine GRAVEL bec. coarse SAND & fine GRAVEL
		NOT BOTTOMED

CB-5 G.R.: NO 0648 1883
G.L.: 10.6m

278	7.8	Brownish blue-grey silty CLAY (carse)
286	7.7	Silty PEAT
290	7.7	Peat-silt TRANSITION
310	7.5	Pale grey mic. SILT or clayey SILT
315	7.4	Dry, tough mic. yellowish-brown silty fine SAND, some fine GRAVEL
		NOT BOTTOMED

CB-6 G.R.: NO 0651 1880
G.L.: 10.9m

205	8.9	Grey-brown bec. bluish-grey silty CLAY (carse)
215	8.8	Brown clayey fine GRAVEL bec. coarse SAND & fine GRAVEL
		NOT BOTTOMED

CB-7 G.R.: NO 0649 1882
G.L.: 10.7m

337	7.4	Silty CLAY & clayey SILT (carse)
346	7.2	Yellowish-brown fine-med. SAND & fine GRAVEL
		NOT BOTTOMED

AREA D

DB-1 G.R.: NO 2042 2234
G.L.: 10.3m

213	8.2	Blue-grey silty CLAY (carse)
220	8.1	Clay-peat TRANSITION
233	8.0	Dry compact wood PEAT
280	7.5	Grey mic. silty fine SAND
		NOT BOTTOMED

DB-2 G.R.: NO 2057 2268
G.L.: 10.7m

386	6.9	Grey silty CLAY (carse)
389	6.8	Clay-sand TRANSITION
395	6.8	Grey silty fine SAND
		NOT BOTTOMED

DB-3 G.R., NO 2051 2257
G.L.: 10.2m

292	7.3	Blue-grey silty CLAY (carse)
413	6.1	Dry compact PEAT
433	5.9	Grey mic. silty SAND
		NOT BOTTOMED

DB-4 G.R.: NO 2041 2290
G.L.: 11.4m

156	9.9	Soft surface PEAT
243	9.0	Soft silty CLAY (carse)
386	7.6	Dry compact PEAT
400	7.4	Grey silty fine SAND
		NOT BOTTOMED

DB-5 G.R.; NO 2049 2263
G.L.: 10.7m

147	9.2	Soft grey silty CLAY (carse)
160	9.1	Compact PEAT
280	7.9	Yellowish-grey silty fine SAND
		NOT BOTTOMED

DB-6 G.R.: NO 2050 2262
G.L.: 10.4m

223	8.2	Soft grey silty CLAY (carse)
278	7.6	Dry compact PEAT
330	7.1	Grey mic. silty fine SAND
		NOT BOTTOMED

DB-7 G.R.: NO 2067 2037
G.L.: 9.8m

492	4.9	Grey silty CLAY (carse)
495	4.9	Clay-peat TRANSITION
516	4.7	Compact PEAT
530	4.5	Pale pinkish-grey clayey fine GRAVEL
		NOT BOTTOMED

DB-8 G.R.: NO 2066 2028
G.L.: 9.6m

690	2.7	Grey silty CLAY (carse)
698	2.6	Clay-peat TRANSITION
752	2.1	Tough compact wood PEAT
		NOT BOTTOMED

DB-9 G.R.: NO 2067 2038
G.L.: 10.0m

389	6.1	Firm CLAY (carse); abundant woody veg. rems esp. nr. base
400	6.0	Grey mic. med. SAND
		NOT BOTTOMED

DB-10 G.R.: NO 2518 2780
G.L.: 10.3m

60	9.7	Grey/reddish-brown sandy CLAY
124	9.1	Reddish-brown tough silty CLAY, lenses of crimson coarse SAND & occ. fine angular GRAVEL
		Stopped by stone(s) at 124

DB-11 G.R.: NO 2516 2784
G.L.: 10.3m

80	9.5	Grey sandy silty CLAY (carse)
206	8.3	Tenacious brown-grey CLAY bec. bluish, with f. abundant scattered fine GRAVEL
		NOT BOTTOMED

DB-12 G.R.: NO 2509 2804
G.L.: 10.3m

200	8.3	Blue-grey mic. sandy clayey SILT
		changing progressively to:-
625	4.0	Dark grey mic. SILT, more clayey below 500-510
631	4.0	Greyish-red coarse gritty SAND
		NOT BOTTOMED

DB-14 G.R.: NO 2127 2033
G.L.: 9.2m

284	6.4	Grey mic. silty CLAY (carse)
294	6.3	Grey mic. silty fine SAND
555	3.7	Grey silty CLAY (carse)
629	2.9	Dry compact PEAT
634	2.9	Grey mic. silty fine SAND with some fine GRAVEL
		NOT BOTTOMED

DB-15 G.R.: NO 2128 2024
G.L.: 9.4m

633	3.1	Grey silty CLAY (carse)
640	3.0	Clay-peat TRANSITION
720	2.2	Tough compact PEAT
737	2.1	Grey mic. SAND & GRAVEL NOT BOTTOMED

DB-16 G.R.: NO 2131 2005
G.L.: 9.4 m

366	5.8	Brown-grey clayey SILT (carse), changing to:-
537	4.0	Silty fine SAND NOT BOTTOMED

DB-17 G.R.: NO 2130 2014
G.L.: 9.4 m

680	2.6	Grey silty CLAY (carse)
703	2.3	Clay-peat TRANSITION
713	2.2	Woody PEAT.NOT BOTTOMED

DB-18 G.R.: NO 2659 2914
G.L.: 9.8 m

316	6.7	Grey silty CLAY (carse)
331	6.5	F. soft PEAT
350	6.3	Grey mic. clayey SILT NOT BOTTOMED

DB-19 G.R.: NO 2651 2938
G.L.: 10.2 m

213	8.1	Grey silty CLAY (carse)
224	8.0	Soft clayey PEAT
259	7.6	Blue-grey mic. CLAY NOT BOTTOMED

DB-20 G.R.: NO 2674 2883
G.L.: 10.1 m

267	7.4	Grey silty CLAY (carse)
271	7.4	PEAT
330	6.8	Grey v.mic. silty fine SAND. NOT BOTTOMED

DB-21 G.R.: NO 2365 2610
G.L.: 10.6 m

30	10.3	SAND & fine GRAVEL
119	9.5	Grey silty CLAY (carse)
179	8.9	Grey-brown v.mic. SILT NOT BOTTOMED

DB-22 G.R.: NO 2132 1996
G.L.: 9.3 m

320	6.1	Grey silty CLAY (carse)
486	4.5	V. mic. sandy SILT NOT BOTTOMED

DB-23 G.R.: NO 2134 1978
G.L.: 9.4 m

800	1.4	Grey mic. sandy SILT/ silty CLAY (carse). Veg. below 740. NOT BOTTOMED

DB-24 G.R.: NO 2686 2853
G.L.: 9.9 m

617	3.8	Grey silty CLAY (carse)
626	3.7	Clay-peat TRANSITION
656	3.4	Compact woody PEAT
658	3.4	Peat-sand TRANSITION
675	3.2	Grey mic. silty fine SAND. NOT BOTTOMED

DB-25 G.R.: NO 2755 2751
G.L.: 9.8 m

470	5.1	Grey silty CLAY (carse)
475	5.0	Compact PEAT
505	4.7	Grey mic. clayey SILT
525	4.5	Grey mic. silty fine SAND. NOT BOTTOMED

DB-26 G.R.: NO 2718 2778
G.L.: 9.6 m

243	7.2	Grey silty CLAY (carse)
249	7.1	Silty PEAT
282	6.8	Stiff pale blue CLAY
300	6.6	Firm grey mic. SILT, black (veg.?) staining
308	6.5	Soft brown silty CLAY
330	6.3	Stiff grey mic. silty fine SAND, black stains NOT BOTTOMED

DB-27 G.R.: NO 2714 2795
G.L.: 9.8 m

180	8.0	Grey silty CLAY (carse)
185	8.0	V.mic. grey fine SAND
320	6.6	Same as 0-180
362	6.2	Brown-grey mic. clayey SILT/silty CLAY
410	5.7	Red-brown mic. silty fine SAND, fine GRAVEL NOT BOTTOMED

DB-28 G.R.: NO 2804 2604
G.L.: 9.1 m

375	5.3	Grey silty CLAY (carse)
497	4.1	Grey mic. silty SAND, shells below 400
731	1.8	Grey silty CLAY (carse)
750	1.6	Compact PEAT NOT BOTTOMED

DB-29 G.R.: NO 2789 2635
G.L.: 9.5 m

464	4.9	Grey silty CLAY (carse)
476	4.8	Grey mic. fine shelly SAND
678	2.8	Grey silty CLAY (carse)
683	2.7	Clay-peat TRANSITION
703	2.5	Compact PEAT
710	2.5	Blue-grey stiff CLAY
730	2.2	Grey v.mic. clayey SILT NOT BOTTOMED

DB-30 G.R.: NO 2378 2626
G.L.: 10.4 m

81	9.6	Grey silty CLAY (carse)
180	8.6	Grey v.mic. fine sandy SILT. NOT BOTTOMED

DB-31 G.R.: NO 2375 2629
G.L.: 10.4 m

50	9.9	Grey silty CLAY (carse)
100	9.4	Brown v.mic. SILT NOT BOTTOMED

DB-32 G.R.: NO 2361 2643
G.L.: 10.1 m

310	7.0	Grey silty CLAY (carse)
322	6.9	Silty PEAT with wood
339	6.7	Med.-coarse SAND NOT BOTTOMED

DB-33 G.R.: NO 2647 2943
G.L.: 10.4 m

123	9.1	Grey silty CLAY (carse)
136	9.0	Clay-peat TRANSITION
140	9.0	PEAT
159	8.8	Blue v.stiff CLAY NOT BOTTOMED

DB-34 G.R.: NO 2646 2947
G.L.: 10.3 m

126	9.1	Grey silty CLAY (carse)
144	8.9	Blue stiff CLAY
159	8.8	Brown mic. clayey SILT/ silty CLAY NOT BOTTOMED

DB-35 G.R.: NO 2652 2933
G.L.: 10.2 m

305	7.1	Grey silty CLAY (carse)
342	6.8	Grey mic. silty fine SAND/sandy SILT NOT BOTTOMED

DB-36 G.R.: NO 2655 2926
G.L.: 10.1 m

370	6.4	Grey silty CLAY (carse)
394	6.2	Grey med. SAND & fine GRAVEL NOT BOTTOMED

DB-37 G.R.: NO 2344 2659
G.L.: 10.6 m

131	9.3	Grey silty CLAY (carse)
179	8.8	Grey v.mic. fine sandy SILT. NOT BOTTOMED

DB-38 G.R.: NO 2348 2656
G.L.: 10.5 m

112	9.4	Blue-grey silty CLAY (carse)
159	8.9	Reddish grey mic. clayey SILT, some fine GRAVEL NOT BOTTOMED

DB-39 G.R.: NO 2352 2651
G.L.: 10.2 m

276	7.5	Blue-grey silty CLAY (carse)
379	6.4	Grey v.mic. fine sandy SILT NOT BOTTOMED

DB-40 G.R.: NO 2337 2666
G.L.: 10.5m

105 9.4 Blue-grey silty CLAY (carse)
119 9.3 Dry PEAT
179 8.7 Blue-grey v. mic. clayey SILT with veg. rems.
NOT BOTTOMED

DB-41 G.R.: NO 2330 2673
G.L.: 10.2m

50 9.7 Soil, brown SAND & fine GRAVEL
60 9.6 Grey silty CLAY (carse)
144 8.7 V. stiff pale grey clayey SILT
NOT BOTTOMED

DB-42 G.R.: NO 2334 2670
G.L.: 10.1m

91 9.2 Grey silty CLAY (carse)
130 8.8 Peaty SILT/silty PEAT
147 8.7 Grey mic. fine SAND
NOT BOTTOMED

DB-43 G.R.: NO 2326 2677
G.L.: 10.1m

30 9.7 Sandy SOIL
100 9.1 V. stiff pale grey mic. clayey SILT with scattered fine GRAVEL
109 9.0 Pale blue stiff CLAY
NOT BOTTOMED

DB-44 G.R.: NO 2367 2636
G.L.: 10.0m

355 6.4 Grey silty CLAY (carse)
364 6.3 Tough pale grey mic. fine sandy SILT with included grit
NOT BOTTOMED

DB-45 G.R.: NO 2381 2623
G.L.: 10.1m

30 9.8 Sandy SOIL
61 9.4 Brownish-grey CLAY (carse)
91 9.1 Pinkish brown-grey v. mic. silty fine SAND
NOT BOTTOMED

DB-46 G.R.: NO 2395 2609
G.L.: 10.6m

91 9.7 Pinkish grey v. mic. silty fine SAND
NOT BOTTOMED

DB-47 G.R.: NO 2392 2612
G.L.: 10.6m

41 10.2 Soil & grey sandy silty CLAY (carse)
91 9.7 Pinkish-grey v. mic. silty fine SAND
NOT BOTTOMED

DB-48 G.R.: NO 2393 2771
G.L.: 10.5m

209 8.4 Brownish blue-grey silty CLAY (carse)
229 8.3 Fibrous woody PEAT
243 8.1 Pale blue-grey mic. silty CLAY
NOT BOTTOMED

DB-49 G.R.: NO 2391 2772
G.L.: 10.4m

206 8.3 Grey silty CLAY (carse)
234 8.0 Pale blue-grey mic. clayey SILT
NOT BOTTOMED

DB-50 G.R.: NO 2386 2774
G.L.: 10.4m

30 10.1 Sandy stony SOIL
156 8.9 Grey silty CLAY (carse)
161 8.8 Peaty silty CLAY
189 8.5 Pale blue-grey mic. clayey SILT
NOT BOTTOMED

DB-51 G.R.: NO 2384 2775
G.L.: 10.6m

30 10.3 Sandy stony SOIL
137 9.2 Grey silty CLAY (carse)
141 9.1 Clay-peat TRANSITION
162 8.9 Dry compact PEAT
200 8.6 Stiff pale blue mic. silty CLAY; layer of fine SAND 176-181
NOT BOTTOMED

DB-52 G.R.: NO 2382 2776
G.L.: 11.0m

46 10.6 Sandy stony SOIL
100 10.0 Grey silty CLAY (carse)
109 9.9 PEAT
159 9.4 Stiff pale blue-grey, bec. pale pinkish brown, silty CLAY
NOT BOTTOMED

DB-53 G.R.: NO 2389 2773
G.L.: 10.3m

138 8.9 Silty CLAY (carse)
164 8.7 Dry compact PEAT
190 8.4 Stiff pale blue-grey mic. sandy clayey SILT
NOT BOTTOMED

DB-54 G.R.: NO 2398 2769
G.L.: 10.0m

127 8.7 Silty CLAY (carse)
138 8.6 Dry compact woody PEAT
159 8.4 Stiff pale blue mic. CLAY
NOT BOTTOMED

DB-55 G.R.: NO 2403 2767
G.L.: 10.1m

111 9.0 Silty CLAY (carse)
Gradual change to:
290 7.2 Pinkish blue-grey mic. silty fine SAND/sandy SILT
309 7.0 V. stiff pale pinkish-grey mic. silty fine SAND
NOT BOTTOMED

DB-56 G.R.: NO 2416 2761
G.L.: 10.1m

387 6.2 Silty CLAY (carse)
390 6.2 Clay-peat TRANSITION
412 5.9 Dry compact woody PEAT
439 5.7 Pale blue-grey v. mic. silty fine SAND occ. wood frags.
NOT BOTTOMED

DB-57 G.R.: NO 2407 2765
G.L.: 10.2m

69 9.5 Silty CLAY (carse)
164 8.5 Pale pinkish-grey fine SAND
NOT BOTTOMED

DB-58 G.R.: NO 2412 2763
G.L.: 10.2m

295 7.3 Sandy silty CLAY (carse)
389 6.3 Mic. pale pinkish-grey silty fine SAND
NOT BOTTOMED

DB-59 G.R.: NO 2401 2768
G.L.: 10.1m

164 8.4 Blue-grey silty CLAY (carse)
209 8.0 Pinkish-grey mic. clayey SILT & silty fine SAND
NOT BOTTOMED

DB-60 G.R.: NO 2476 2733
G.L.: 10.4m

91 9.5 Red SAND with grit & fine GRAVEL
NOT BOTTOMED

DB-61 G.R.: NO 2472 2735
G.L.: 10.4m

69 9.7 Grey silty CLAY (carse)
110 9.3 Reddish-brown plastic CLAY
NOT BOTTOMED

DB-62 G.R.: NO 2468 2736
G.L.: 10.5m

69 9.8 Grey silty CLAY (carse)
76 9.7 Red gritty SAND & fine GRAVEL
110 9.4 V. tough reddish-brown sandy clayey SILT/silty clayey fine SAND
NOT BOTTOMED

DB-63 G.R.: NO 2463 2739
G.L.: 10.5m

53 10.0 Whitish-grey silty CLAY (carse)
112 9.4 Reddish-brown, with pale blue-grey streaks, mic. clayey SILT/silty CLAY; probably laminated
115 9.4 Red gritty SAND
Stopped by stone or drain at 115

DB-64 G.R.: NO 2459 2741
G.L.: 10.1m

160 8.5 Blue-grey silty CLAY (carse)
189 8.2 V. stiff reddish-brown silty CLAY
NOT BOTTOMED

DB-65 G.R.: NO 2454 2743
G.L.: 10.2m

165 8.5 Grey silty CLAY (carse)
189 8.3 V. tough brownish-grey v. mic. sandy SILT
NOT BOTTOMED

DB-66 G.R.: NO 2450 2745
G.L.: 10.3m

91 9.3 Grey silty CLAY (carse)
129 9.0 Stiff reddish-brown, with grey streaks, silty CLAY; probably laminated.
NOT BOTTOMED

DB-67 G.R.: NO 2445 2747
G.L.: 10.2m

151 8.7 Grey silty CLAY (carse)
156 8.7 Silty woody PEAT
164 8.6 Pale grey mic. SILT, some woody rems.
171 8.5 Pale blue mic. silty CLAY
189 8.3 V. stiff reddish-brown CLAY
NOT BOTTOMED

DB-68 G.R.: NO 2441 2749
G.L.: 9.9m

357 6.3 Grey silty CLAY (carse)
381 6.1 Pale brown-grey v. mic. SILT
NOT BOTTOMED

DB-69 G.R.: NO 2437 2751
G.L.: 10.0m

486 5.2 Grey silty CLAY (carse)
509 4.9 Grey mic. sandy SILT/silty fine SAND
NOT BOTTOMED

DB-70 G.R.: NO 2427 2755
G.L.: 10.1m

596 4.2 Grey sandy silty CLAY (carse)
600 4.1 Dk. grey coarse gritty SAND & fine GRAVEL
NOT BOTTOMED

DB-71 G.R.: NO 2049 2263
G.L.: 10.9m

53 10.4 Soil, & brown-grey silty fine SAND
160 9.3 V. soft blue-grey silty CLAY (carse)
175 9.2 Grey mic. fine SAND
NOT BOTTOMED

DB-72 G.R.: NO 2048 2263
G.L.: 11.2m

61 10.6 Grey-brown mic. fine SAND
91 10.3 Soft blue-grey silty CLAY (carse)
NOT BOTTOMED

DB-73 G.R.: NO 2048 2264
G.L.: 11.5m

84 10.7 Pale brown mic. fine SAND bec. pale brownish-grey
91 10.6 Silty PEAT
NOT BOTTOMED

DB-74 G.R.: NO 2047 2264
G.L.: 12.1m

69 11.4 Pale brown mic. fine SAND
130 10.8 Steel-grey mic. fine SAND
135 10.8 Silty PEAT/v. peaty SILT
150 10.6 Pale grey mic. silty fine SAND
NOT BOTTOMED

DB-75 G.R.: NO 2047 2264
G.L.: 11.7m

69 11.0 Yellowish-brown mic. fine SAND
91 10.8 PEAT
127 10.5 Yellowish-brown mic. fine SAND
167 10.1 Dk. brown silty PEAT
187 9.9 Pale grey mic. silty fine SAND
NOT BOTTOMED

DB-76 G.R.: NO 2046 2264
G.L.: 12.7m

337 9.3 Grey mic. fine SAND/silty fine SAND
NOT BOTTOMED

Abbreviations used in Appendix II

bec. = becoming
dk. = dark
f. = fairly
mic. = micaceous
rems. = remains
v. = very
veg. = vegetal, vegetation

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